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5G NR PRIVATE NETWORK COST EVALUATION IN TELECOMMUNICATIONS, CONSTRUCTION AND POWER DISTRIBUTION

Danila Kondrashov [1]
Evgeniy Rogozhnikov
Renat Abenov
Serafim Novichkov
Evgeniy Ageev
Andrey Zhalsaraev

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A B S T R A C T

In the 5G concept, nonpublic networks can be used in any private enterprises. However, the most relevant at present is the introduction of private networks in priority sectors of the economy. These are such sectors as communications and telecommunications, production and distribution of electricity, as well as housing construction. The paper considers four scenarios for calculating the total cost of a 5G network, as well as three scenarios for deployment in various sectors. For calculations, the authors define the concepts of CAPEX and OPEX, and present the architecture of the 5G network. The calculation was performed by the optimal method in each individual scenario. The results of the work were obtained by mathematical modeling in the Matlab environment.

1. INTRODUCTION

The ongoing digitalization of manufacturing is key to driving the next generation of more efficient, connected, and supported industrial systems. This new generation, called “Industry 4.0”, is accompanied by new opportunities that will allow enterprises in various industries from logistics to manufacturing to increase the flexibility and productivity of their technological processes. The use of 5G technology to build enterprise networks provides the necessary functionality. However, the architecture of the network being created is always tied to the tasks that need to be solved and these tasks vary from industry to industry.

A private mobile network is one in which the infrastructure is used exclusively by devices authorized by the organization that owns the network. Typically, the infrastructure is deployed in an area owned by the enterprise. Devices registered on public mobile networks do not work on nonpublic networks other than those that have been authorized. Virtualized private networks (also called Dedicated Networks) can also be used by industrial enterprises, typically using separate 5G layers, over a public mobile network. In this case, the enterprise receives most of the benefits of a private network, while avoiding the complexity of the costs of acquiring, installing equipment and maintaining.

[1] Corresponding author: Danila Kondrashov
Email: danila.a.kondrashov@tusur.ru

The purpose of this work is to estimate and optimize the costs of implementing nonpublic networks in scenarios that are suitable for the listed priority areas. To achieve this goal, three main tasks have been set:

- Determine the capital and operating costs of deploying 5G networks;
- Calculate the cost of deployment in the selected scenarios;
- Determine the cost of deploying a private 5G NR network for various sectors of the economy.

An analysis of publications showed that such works describing scenarios and cost optimization methods are rare. Some papers contain descriptions of various deployment scenarios for 5G networks, others describe methods for optimizing deployment costs. The work (Rostami, 2019) considers the implementation of private 5G networks in various industries and provides a systematic classification of potential deployment architectures and exploitation models. In addition, an extensive set of performance metrics is defined and a comparative analysis of identified deployment and operational patterns is presented. (Ordonez-Lucena, Chavarria, Contreras, & Pastor, 2019) provide an overview of non-public 5G networks and analyze their applicability to the Industry 4.0 ecosystem. Based on the 3GPP Rel-16 specifications, they consider a range of deployment options suitable for non-public networks and discuss their integration with public networks of mobile operators. Also, the paper compares deployment scenarios with respect to their feasibility and evaluates their feasibility according to various criteria, including technical, regulatory and commercial aspects. The results of this analysis will help industry participants interested in non-public networks to choose the most appropriate deployment option for their use cases. (Yeganeh & Vaezpour, 2016), (Klinkowski, 2018), (Tonini, Raffaelli, Wosinska, & Monti, 2019) and (Masoudi, Lisi, & Cavdar, 2020) investigated cost optimization for 5G network deployment using linear programming methods. The scenarios described in the listed works don't fall under the criteria of this work. This paper discusses four scenarios for building a 5G network architecture, and also provides a rationale for choosing individual scenarios for each sector of the economy.

2. CAPITAL AND OPERATING COSTS FOR 5G NR NONPUBLIC NETWORKS.

2.1 The terms CAPEX, OPEX and TCO

Any enterprise has many expense items such as renting premises, offices, purchasing materials for production and paying salaries. To simplify financial management, such a concept as TCO (Total Cost of Ownership) was introduced, which includes CAPEX (Capital Expenditures) and OPEX (Operational Expenditures). The Total Cost of Ownership (TCO) is a value that reflects the total cost of the target costs that must be borne by the owner from the moment of taking possession until the moment he leaves possession and fully fulfills his obligations associated with ownership.

CAPEX is the cost of purchasing building materials or equipment. In this paper, CAPEX includes:

- cost of radio access network equipment including RU (radio unit), DU (distributed unit) and CU (centralized unit);
- cost of the 5G network core;
- cost of cooling equipment;
- costs for licensed software;
- cost of erecting a mast.

OPEX is the cost of day-to-day tasks such as rent and utilities, employee salaries, taxes, etc. In this paper, OPEX includes:

- electricity costs;
- operating and maintenance costs;
- cost of renting equipment and sites;
- costs for updating licensed software;
- the cost of renting an area for hosting sites.

2.2 5G network architecture D-RAN, C-RAN and Open RAN

The cost of deploying a 5G network is largely determined by the architecture of the radio access network. There are several types of RAN construction, D-RAN, C-RAN and Open RAN are considered in the work. D-RAN is a type of RAN architecture in which the processing equipment (DU and CU) is located directly beside to the mast, antenna and RU (Xiao-hu & Xin-sheng, 2004). Each base station thus processes information independently of other stations. The DU/CU unit, after processing, transmits the data to the core of the 5G network.

Figure 1 shows a graphical representation of the 5G D-RAN network.

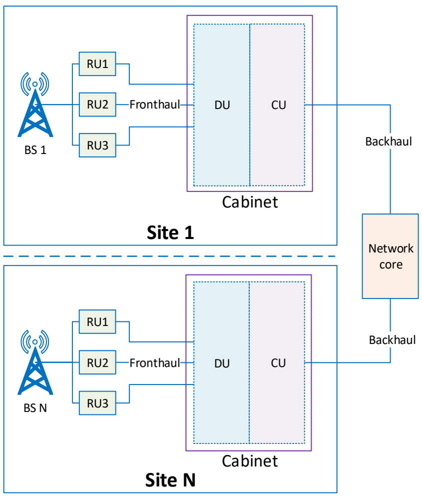

Figure 1. Graphical representation of a 5G D-RAN network

C-RAN (Centralized RAN) is a type of RAN architecture in which only the RU, mast and antenna are located at the base station site, while the DU and CU units are deployed in the data center and process several base stations at once (Wu, Zhang, Hong, & Wen, 2015). Figure 2 shows a graphical representation of the 5G C-RAN network.

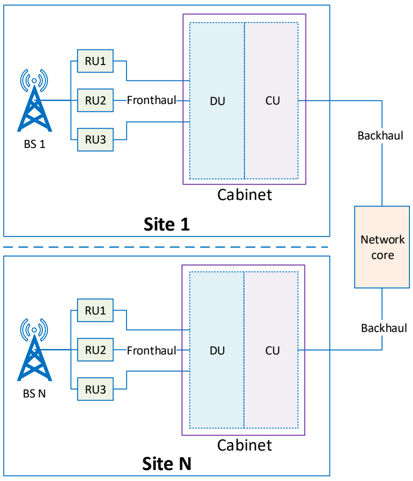

Figure 2. Graphical representation of a 5G C-RAN network

The choice of architecture type depends on many factors, and each type has a number of advantages and disadvantages.

The advantages of C-RAN over D-RAN are:

- Equipment costs less. Since one DU and CU processing unit can serve several base stations at once, the overall cost of purchasing equipment is reduced;
- Lower energy, maintenance and cooling costs. This is due to the fact that temperature-sensitive equipment is combined into one DPC (data processing center). It is much easier and cheaper to adjust the climatic conditions in the DPC than in each separate cabinet.

The disadvantages of C-RAN compared to D-RAN are:

- Dependence of a large number of base stations on the data center. Malfunctions in the data center can lead to the incapacity of all stations that are connected to it.

Open RAN is a type of RAN architecture in which the functions of computing equipment are virtualized, i.e. implemented in software (Singh, Singh, & Kumbhani, 2020). The Open RAN architecture is very similar to the C-RAN architecture. However, Open RAN eliminates the need for specialized hardware and the proprietary Fronthaul interface. Instead of specialized hardware, standard server hardware and software are used, and all interfaces between units are open.
The advantages of Open RAN over D-RAN and C-RAN are:

- Disaggregation of software and hardware;
- Ability to dynamically allocate resources depending on network load;
- Network flexibility and scalability;
- Ability to purchase modules from multiple manufacturers at better prices due to open interfaces;
- Lack of multiple growth for maintenance and operation in the post-warranty period.

This paper considers in detail the D-RAN and Open RAN architectures. This choice was made because D-RAN reflects the traditional approach to building radio access networks used in LTE networks, and Open RAN is a new one, offered exclusively for 5G deployment.

3. CALCULATING THE TOTAL COST OF A 5G NETWORK FOR DIFFERENT SCENARIOS

The 5G NR standard offers very flexible scenarios for implementing private networks. According to 3GPP, deployable networks can be divided into two categories: public land mobile networks and private networks. The first type provides network services for public use and is operated by the operator. The second provides coverage of private territory and provides network services to all devices in that territory. This includes not only subscriber terminals, but also sensors, manufacturing robots, autopilot vehicles, etc.

There are different variants of private network deployment, in which a private network can be built anew and hardware belongs to the private network owner, or some hardware can be rented from the operator. There is also a scenario where all network hardware is leased.
Basic elements of hardware, from which private network is built: 5G Core (5GC) and base station, consisting of radio module (RU), Distributed Unit (DU) and Centralized Unit (CU).

In our work, we will consider the following network deployment scenarios:

- Fully isolated private 5G network;
- Private 5G network with leased core and private base stations;
- Private 5G network with leased base stations and a private core;
- Fully leased private 5G network.

For each scenario, there is a brief description with advantages and disadvantages, as well as formulas for calculating capital and operating costs. Table 1 shows the distribution of components for all scenarios

Table 1. Distribution of components of all scenarios.

Element	Scenario 1	Scenario 2	Scenario 3	Scenario 4
RU	Private	Private	Leased	Leased
DU	Private	Private	Leased	Leased
CU	Private	Private	Leased	Leased
5G Core	Private	Leased	Private	Leased

3.1 Scenario 1. A fully isolated 5G private network

In Scenario 1, the Total Cost Ownership (TCO) calculation is performed for the case of a completely isolated private 5G network, where all hardware is purchased by the owner. In this case, the company itself deploys the entire 5G network on its territory. If the country provides for the use of private frequency bands, the enterprise can use its own. Private enterprises can create their own private networks, and operators can create networks to lease to other enterprises. The scenario is the most time-consuming of all presented. This scenario provides all the benefits of using 5G networks and full autonomous network operation in case of an operator outage.

In terms of implementation in a practical sense, both D-RAN and Open RAN architecture are applicable in this scenario. Therefore, the calculations related to the isolated network are made taking into account both options.

The advantages:

- Confidentiality and security. Private network is physically separated from the public network and provides full data protection (data traffic, information signatures and operational information from private network devices, all processed and stored only within the enterprise, no information leaks)
- Ultra-low latency. Since network latency between the device and the server does not exceed a few milliseconds, URLLC (Ultra-Reliable Low Latency Communication) services can be used.
- Independence of the mobile operator's performance. Even in the event of mobile carrier outages, the enterprise's 5G network continues to work.

Disadvantages:

- Cost of deployment. It's not easy for an average enterprise to buy and deploy a full-fledged 5G network at their own expense. Especially for small businesses.
- Operational staffing. The need for engineers with sufficient expertise in installing and maintaining 5G networks.

Calculating the Total Cost of Ownership for a 5G network (D-RAN)

The total cost of ownership in this scenario consists of capital expenditures (CAPEX) and operating expenditures (OPEX), which are calculated using the formulas below.

$$CAPEX^{5G}_{D-RAN} = N_{site} \cdot (C_{site} + C_{CWsite}) + C_{optic} + C_{5GC} + C^{cool}_{5GC} + C_{CWcore} \quad (1)$$

where N_{site} – the number of sites;

C_{site} – the cost of installing the site;

C_{optic} – the cost of the optical line;

C_{CWsite} – CW (Commissioning Works) costs per site, calculated as 20% of the cost of the site:

$$C_{CWsite} = 0.2 \cdot (N_{RU} \cdot C_{RU} + C_{DU/CU} + C_{CPRI}) \,. \quad (2)$$

C_{5GC} – cost of 5G core hardware;

C^{cool}_{5GC} – the cost of the core cooling unit;

C_{CWcore} – the cost of commissioning work with the network core, equal to 20% of the cost of the core.

The cost of installing the site C_{site} is calculated by the formula:

$$C_{site} = C_{DU/CU} + N_{RU} \cdot C_{RU} + C_{mast} + C_{cool} + C_{CPRI} \,. \quad (3)$$

C_{CPRI} – CPRI (Common Public Radio Interface) board cost;

$C_{DU/CU}$ – CU module cost, which is the sum of DU – C_{DU} and CU – C_{CU} cost and is calculated as $C_{DU/CU} = C_{DU} + \frac{1}{2} C_{CU}$;

N_{RU} – the number of RU;

C_{mast} – the cost of erecting the mast of the base station;

C_{cool} – the cost of the cooling unit.

The cost of the optical line is calculated as follows:

$$C_{optic} = C_{dig} \cdot \left(\frac{L^{front}_{summ}}{N_{RU}} + L^{back}_{summ} \right) + C_{rol} \cdot (L^{front}_{summ} + L^{back}_{summ}) \,. \quad (4)$$

where C_{dig} – the cost of one kilometer of trench;

L^{front}_{summ} – total length of the fronthaul line;

L^{back}_{summ} – the total length of the backhaul line;

C_{rol} – the cost of purchasing and rolling out one kilometer of fiber-optic line.

The OPEX calculation is for one year. This calculation includes energy costs, operation and maintenance costs, fiber and site rental costs, as well as employee salaries, support and network deployment costs.

$$OPEX^{5G}_{D-RAN} = C_{W/h} \cdot P + N_{site} \cdot C_{rent} + L_{optic} \cdot C_{lease} + C_{OEM} + C_{wages} + C_{soft} \,. \quad (5)$$

where $C_{W/h}$ – cost per W*h;

P – total power consumption;

C_{soft} – the cost of updating the software, calculated as 30% of the cost of the software:

$$C_{soft} = 0.3 \cdot (N_{site} (C_{RU} \cdot N_{RU} + C_{DU/CU}) + C_{5GC}) \,. \quad (6)$$

L_{optic} – the total length of the optical line, calculated as:

$$L_{optic} = L_{summ}^{front} + L_{summ}^{back} \quad . (7)$$

C_{lease} – annual maintenance of optical fiber per kilometer;

C_{rent} – site rental cost;

C_{OEM} – annual operation and maintenance;

C_{wages} – annual employee salaries, calculated as:

$$C_{wages} = N_{month} \cdot wage \cdot N_{staff} \quad . (8)$$

where N_{month} – number of hours per year;

$wage$ – the salary per month of one employee;

N_{staff} – the number of employees (1 employee for every 500 sites, minimum 1).

The total power consumption is defined as 60% of the total power consumption summed up from the power consumed by the network core and the power consumed by the sites, taking into account the number of hours per year:

$$P = 0.6 \cdot N_{hour/year} \cdot (N_{site} \cdot P_{site} + P_{5GC} + P_{5GC}^{cool}) \quad . (9)$$

where $N_{hour/year}$ – number of hours per year;

P_{5GC} – power consumed by the network core;

P_{5GC}^{cool} – power consumed by the core cooling unit.

The total power consumed by the site P_{site}, is calculated using the formula:

$$P_{site} = N_{RU} \cdot P_{RU} + P_{DU/CU} + P_{cool} \quad . (10)$$

where N_{RU} – number of RU modules;

P_{RU} – power consumed by one RU module;

$P_{DU/CU}$ – power consumption DU/CU

P_{cool} – consumed power of the cooling unit.

Calculation of annual O&M costs is calculated as a percentage of the cost of all used equipment and is calculated by the formula

$$C_{OEM} = C_{percent} \cdot (N_{site} \cdot (N_{RU} \cdot C_{RU} + C_{DU/CU} + C_{CPRI}) + C_{5GC}), \quad . (11)$$

where $C_{percent}$ – a percentage for operation and maintenance, equal to 10% of the total cost of the hardware.

Calculation of the total cost of ownership of a 5G network (Open RAN).

To calculate CAPEXa for Open RAN architecture and split RU/DU by split 7.2, the following formula will be used:

$$CAPEX_{O-RAN}^{5G} = N_{DPC} \cdot (C_{DPCbuild} + C_{DPCequip} + C_{CW}^{DPC}) + N_{site} \cdot (C_{site}^{O-RAN} + C_{CW}^{site}) + C_{optic} + C_{soft} + C_{5GC} + C_{5GC}^{cool} + C_{CWcore} \quad . (12)$$

where N_{DPC} – is the number of necessary data centers and is calculated as:

$$N_{DPC} = ceil\left(\frac{N_{site}}{N_{site}^{DPC}}\right) \quad . (13)$$

where $ceil$ – where ceil is the rounding operation upwards;

N_{site}^{DPC} – the number of sites located within a radius of 15 km from the data center.

The number of required racks in one data center is calculated as:

$$N_{rack}^{DPC} = ceil\left(\frac{\left(ceil\left(N_{site}^{DPC} \cdot \frac{N_{RU}}{N_{DU}^{RU} \cdot N_{vDU\to DU}}\right) + ceil\left(N_{site}^{DPC} \cdot \frac{N_{RU}}{N_{DU}^{RU} \cdot N_{CU}^{DU} \cdot N_{vCU\to CU}}\right)\right)}{N_{serv}^{rack}}\right) \quad . (14)$$

where N_{DU}^{RU} – number of RU served by one virtual DU;

$N_{vDU\to DU}$ – the number of virtual DUs hosted by one physical DU server;

N_{CU}^{DU} – the number of virtual DUs served by one virtual CU;

$N_{vCU\to CU}$ – number of virtual CUs hosted by one physical CU server;

N_{serv}^{rack} – maximum rack capacity per physical servers.

$C_{DPCbuild}$ – The cost of building a data center, calculated as:

$$C_{DPCbuild} = C_{rack}^{Tier} \cdot N_{rack}^{DPC} \quad . (15)$$

where C_{rack}^{Tier} – the cost of building one data center in terms of one rack for the required level of reliability.

Calculation of the cost of the hardware installed in one data center is performed as follows:

$$C_{DPCequip} = TC_{DU}^{DPC} + TC_{CU}^{DPC} + C_{cool} \quad . (16)$$

where TC_{DU}^{DPC} – the total cost of the server DUs installed in one data center, and is calculated as:

$$TC_{DU}^{DPC} = N_{DU}^{DPC} \cdot (C_{DU}^{IXD} + C_{Ethernet}) \quad . (17)$$

where N_{DU}^{DPC} – the number of DUs in one data center;

C_{DU}^{IXD} – the cost of implementing one DU on the server hardware;

$C_{Ethernet}$ – the cost of the network card.

TC_{CU}^{DPC} – total cost of server CUs installed in one data center, is calculated as:

$$TC_{CU}^{DPC} = N_{CU}^{DPC} \cdot C_{DU}^{IXD} \quad . (18)$$

where N_{CU}^{DPC} – the number of CU in one data center;

C_{CU}^{IXD} – the cost of implementing one CU on the server hardware.

C_{CW}^{DPC} – the cost of commissioning work in one data center, which is 25% of the cost of servers in one data center:

$$C_{CW}^{DPC} = 0.25 \cdot (TC_{DU}^{DPC} / N_{vDU \to DU} + TC_{CU}^{DPC} / N_{vCU \to CU}) \ . (19)$$

C_{site}^{O-RAN} – Open RAN site cost, calculated as:

$$C_{site}^{O-RAN} = N_{RU} \cdot C_{RU} + C_{mast}, \quad . (20)$$

C_{CW}^{site} – the cost of commissioning one site, calculated as 20% of the cost of the site:

$$C_{CW}^{site} = 0.2 \cdot (N_{RU} \cdot C_{RU}), \quad . (21)$$

C_{soft} – the cost of purchasing the software and is calculated as:

$$C_{soft} = N_{site} \cdot N_{RU} \cdot C_{soft}^{RU} + N_{DPC} \cdot (N_{DU}^{DPC} \cdot C_{soft}^{DU} + N_{CU}^{DPC} \cdot C_{soft}^{CU}) + C_{5GCsoft}, \quad . (22)$$

where C_{soft}^{RU} – software cost of one RU;

C_{soft}^{DU} – software cost of one DU;

C_{soft}^{CU} – the cost of the software of one CU;

$C_{5GCsoft}$ – the cost of the 5G core software.

OPEX in this case will be calculated by the formula:

$$OPEX_{O-RAN}^{5G} = C_{W/h} \cdot P + N_{site} \cdot C_{rent}^{site} + L_{optic} \cdot C_{lease} + N_{DPC} \cdot C_{rent}^{DPC} + C_{OEM} + C_{wages} + C_{soft}^{UP}, \quad . (23)$$

where C_{rent}^{site} – the cost of renting a site under the site;

C_{rent}^{DPC} – the cost of renting a site for a data center;

C_{soft}^{UP} – the cost of annual software updates, included in 30% of the cost of software:

$$C_{soft}^{UP} = 0.3 \cdot C_{soft} \quad . (24)$$

The total capacity consumed by the network per year will be calculated as follows:

$$P = 0.6 \cdot N_{year/hour} \cdot (N_{site} \cdot P_{site} + N_{DPC} \cdot P_{DPC} + P_{5GC} + P_{5GC}^{cool}), \ . (25)$$

where P_{DPC} – is the power consumed by one data center, which is calculated according to the formula

$$P_{DPC} = N_{DU}^{DPC} * P_{DU}^{IXD} + N_{CU}^{DPC} * P_{CU}^{IXD} + P_{cool}, \quad . (26)$$

where P_{DU}^{IXD} – consumed power of one DU at the base of server hardware;

P_{CU}^{IXD} – is the power consumed by one DU on the basis of server hardware;

P_{site} – the power consumed by one site, which is calculated as:

$$P_{site} = N_{RU} \cdot P_{RU}, \quad . (27)$$

C_{OEM} – O&M costs, calculated as:

$$C_{OEM} = C_{percent} \cdot (N_{site} \cdot (N_{RU} \cdot C_{RU}) + N_{DPC} \cdot (C_{DPCequip} - C_{cool}) + C_{5GC}) \quad . (28)$$

3.2 Scenario 2. Private: gNB (RU, DU, CU). Rented: 5GC

Under Scenario 2, the full cost of network deployment is calculated for the case where the gNB base station, including the radio module, distributed module and centralized module are private and the 5G core network, including Mobility Management Function (AMF), Session Management Function (SMF)) and User Plane Function (UPF), is owned by the operator.

Advantages:

- The ability to select the location of base stations allows you to deploy a 5G network in hard-to-reach locations.
- Use of licensed spectrum (if the company has its own frequency range).

Disadvantages:

- The cost of purchasing, installing base stations and equipment for them.
- The need to support and upgrade the base stations in accordance with the requirements, as well as changes and upgrades to the technology used by the base station.
- Low security. The data travels from the enterprise to the operator's core and back again.
- The presence of network response latency, depending on the location of the operator's 5G network core. Significant delay leads to the inability to use URLLC services.

Calculating the total cost of ownership of a 5G network (D-RAN)

The difference with scenario 1 in the CAPEX calculation is that the cost of installing the 5G core and the cooling unit for the core is missing here:

$$CAPEX^{5G}_{D-RAN} = N_{site} \cdot (C_{site} + C_{CWsite}) + C_{optic}, \quad (29)$$

The difference with scenario 1 in the OPEX calculation is that the cost of leasing the 5G core $C_{5GCrent}$ will be added to the cost:

$$OPEX^{5G}_{D-RAN} = C_{W/h} \cdot P + N_{site} \cdot (C_{rent} + C_{soft}) + L_{optic} \cdot C_{lease} + C_{OEM} + C_{wages} + C_{5GCrent}, \quad (30)$$

$C_{5GCrent}$ – the cost of renting the 5G core.

This calculation does not include the power consumption of the 5G core, nor does it include the cost of its maintenance. P is the total power consumption:

$$P = 0.6 \cdot N_{hour/year} \cdot N_{site} \cdot P_{site}, \quad (31)$$

C_{OEM} – annual operation and maintenance:

$$C_{OEM} = C_{percent} \cdot N_{site} \cdot (N_{RU} \cdot C_{RU} + C_{DU/CU} + C_{CPRI}) \quad (32)$$

Calculation of the total cost of ownership of a 5G network (Open RAN**)**

To calculate CAPEXa for Open RAN architecture and split RU/DU by split 7.2, the following formula will be used:

$$CAPEX^{5G}_{O-RAN} = N_{DPC} \cdot (C_{DPCbuild} + C_{DPCequip} + C^{DPC}_{CW}) + N_{site} \cdot (C^{O-RAN}_{site} + C^{site}_{CW}) + C_{optic} + C_{soft}, \quad (33)$$

The difference with scenario 1 in the OPEX calculation is that the cost of leasing the 5G core $C_{5GCrent}$ will be added to the cost:

$$OPEX^{5G}_{O-RAN} = C_{W/h} \cdot P + N_{site} \cdot C^{site}_{rent} + L_{optic} \cdot C_{lease} + N_{DPC} \cdot C^{DPC}_{rent} + C_{OEM} + C_{wages} + C^{UP}_{soft} + C_{5GCrent}, \quad (34)$$

The total power consumed by the network per year will be calculated as follows:

$$P = 0.6 \cdot N_{year/hour} \cdot (N_{site} \cdot P_{site} + N_{DPC} \cdot P_{DPC}), \quad (35)$$

C_{OEM} – annual operation and maintenance cost, calculated as:

$$C_{OEM} = C_{percent} \cdot (N_{site} \cdot (N_{RU} \cdot C_{RU}) + N_{DPC} \cdot (C_{DPCequip} - C_{cool})), \quad (36)$$

3.3 Scenario 3. Private: 5GC. Leased: gNB (RU, DU, CU)

Scenario 3 calculates the full cost of network deployment for the case where the gNB base station including radio module, distributed module and centralized module are owned by the operator and the 5G core network including Mobility Management Function (AMF), Session Management Function (SMF)) and User Plane Function (UPF) are private.

Advantages:

- Privacy. Although some of the equipment is leased, it is quite difficult to collect information at the radio access network level, so security is at a high level. Since the 5G network core is private, information signatures and operational information are processed and stored internally, so there are no data leaks.
- Ability to use URLLC services due to low latency. Since the location of the 5G network core is controlled by the enterprise, it can be installed close to the wireless network cell, which will ensure the fastest possible network response.

Disadvantages:

- Having qualified employees with sufficient competence to maintain and operate the 5G core hardware.

Calculation of the total cost of ownership of a 5G network

This scenario assumes that the base station hardware is owned by the operator, so the implementation of the architecture (D-RAN or Open RAN) is independent of the enterprise. The difference with scenario 1 in the CAPEX calculation is that it only considers the cost of the core and associated work:

$$CAPEX^{5G} = C_{5GC} + C_{CWcore} + C_{cool} + C_{DPCbuild}, \quad (37)$$

As a consequence, the difference with scenario 1 in the OPEX calculation is that there is the cost of site rental and associated cooling and fiber optics. It also takes into account the power consumption of the 5G core, as well as the cost of its maintenance and operation.

$$OPEX^{5G} = C_{W/h} \cdot P + C_{siterent} + C_{OEM} + C_{wages}, \quad (38)$$

where $C_{siterent}$ is the cost of leasing the base stations. In turn, the calculation of P will change to the following:

$$P = 0.6 \cdot N_{hour/year} \cdot (P_{5GC} + P^{cool}_{5GC}), \quad (39)$$

Calculation C_{OEM} – the cost of annual operation and maintenance – will also change:

$$C_{OEM} = C_{percent} \cdot C_{5GC} \quad (40)$$

3.4 Scenario 4. Fully leased 5G network

For Scenario 4, full network deployment costs are calculated for the case where communication services and all 5G equipment are fully provided by the operator, including the scenario where the tenant is a virtual mobile network operator. This scenario describes the operation of virtual mobile network operators, but it can be quite successfully applied by any private enterprise for its needs. Moreover, this solution is the most affordable for private enterprises, especially in cases where the deployed private network is needed only for a certain period of time. This solution is especially useful for companies such as city planning companies that leave the site after the work is completed and the facility is handed over.

Advantages:

- No capital investment in infrastructure. Possibility to fully rent an already available 5G network allows companies with small budgets to enter the service market, which is an important factor for new enterprises.
- No need to upgrade hardware when changing technologies.

Disadvantages:

- Low security. Security mechanisms are provided by the service provider and cannot be configured personally for any private network.
- Vulnerability to malfunctions on the operator side. Since all equipment used for a private 5G network is owned by the operator, the speed of troubleshooting is determined by the operator.

Calculation of the total cost of ownership of a 5G network

This scenario also does not involve the choice of D-RAN or Open RAN architecture. In the case of a full equipment lease, the rent calculation does not depend on the cost of the equipment, since the tariff is set by the operator. Since all equipment is leased, there are no capital costs: $CAPEX = 0$.

The operating costs of this scenario depend entirely on the operator's tariff:

$$OPEX = N_{UE} \cdot T_{year} \cdot C_{1Gb} \quad . (41)$$

where N_{UE} – number of user elements;

T_{year} – average annual traffic per subscriber;

C_{1Gb} the cost of one gigabyte of traffic according to the operator's price.

4. ESTIMATING THE DEPLOYMENT COST OF A PRIVATE 5G NR NETWORK FOR VARIOUS SECTORS OF THE ECONOMY

The application of 5G technologies to various sectors of the economy can improve production efficiency and accelerate the pace of development of the industry. But each industry has its own requirements, and therefore the applicability of certain scenarios for deploying a 5G network is different. The following sections describe the application of the 5G network for three priority sectors of the economy: communications and telecommunications, production and distribution of electricity, construction. In each scenario, CAPEX and OPEX costs are estimated. The estimation is based on the cost of equipment and works indicated in Table 2. The table data is current as of August 2022.

Table 2. The main parameters used in the calculations.

Parameter name	Variable name	D-RAN	O-RAN
CAPEX			
Number of RUs per BS, pcs.	N_{RU}	3	3
Acquisition and installation cost of the mast on the site, USD	C_{mast}	15 000	15 000
Single RU cost (D-RAN), USD	C_{RU}	2 000	4 000
Single RU software cost, USD			200
Cost of single DU/CU / virtual DU in terms of one physical server, USD	$C_{DU/CU}$	6 000	3 000
Cost of single virtual DU as a program (O-RAN), USD	C_{soft}^{DU}		400
Cost of single CU / virtual CU in terms of one physical server, USD	C_{CU}	6 000	4 000
Cost of single virtual CU as a program, USD	C_{soft}^{CU}		400
Cost of single CPRI board, USD	C_{CPRI}	2 500	
Cost of single Ethernet board, USD			150
Cooling unit cost for DU/CU, USD	C_{cool}	1500	
Cooling unit power for DU/CU, W*h	P_{cool}	500	
Cooling unit cost for DPC, USD	C_{cool}		5 000
Cost of building a data center in terms of single server rack, USD	C_{rack}^{Tier}		34 852
5G core cost, USD	C_{5GC}	50 000	50 000
Cost of digging 1 km of trench, USD	C_{dig}	3 000	3 000
Cost of purchasing and rolling 1 km of optical fiber, USD	C_{rol}	1 000	1 000
Commission works percentage (CW), %	C_{cw}	20	20

Table 2. The main parameters used in the calculations. (continued)

OPEX			
Cost of 1 Watt*hour, USD	$C_{W/h}$	0.000673	0.000673
Annual maintenance cost for 1 km of optical fiber, USD	C_{lease}	50	50
Annual renting cost of a site for BS/DPC, USD	C_{rent}	5 000	5 000
Monthly wage of one worker, USD	$wage$	2700	2500
Number of workers, people	N_{staff}	1	1
Software update percentage, %	C_{soft}^{UPDATE}	30	30
Percentage of the cost of equipment pledged for its maintenance (OEM), %	$C_{percent}$	10	10
Power consumption of a single RU, W*h	P_{RU}	500	700
Power consumption of a single DU/CU module, W*h	$P_{DU/CU}$	400	
Power consumption of a single virtual DU, W*h	P_{DU}^{IXD}		400
Power consumption of a single virtual CU, W*h	P_{CU}^{IXD}		400
Power consumption of the cooling unit for DPC, Wh	P_{cool}		2000
Power consumption of the network core, W*h	P_{5GC}	500	500
Power consumption of the cooling unit for the network core, W*h	P_{5GC}^{cool}	500	500

4.1 Communications and telecommunications

As an example, let us consider deployment of a virtual mobile operator 5G network. The owner of the physical mobile network usually owns the license for the exclusive use of certain radio spectrum frequencies in the country. This often leads to market monopolization, service degradation or underutilization of radio resources. To solve these problems, many virtual network operators have recently appeared. They use part or all of one or more licenses of the owner, as well as his equipment.

However, building your own infrastructure is always a very expensive undertaking, and in the case of deploying a virtual network for the operator, it is a completely unprofitable scenario. Forward telecom articles (2020) (“Base station of a cellular operator: transformation under 5G and role in the work of MVNO”, n. d.). The largest cellular operators in the Russian Federation - MTS, Beeline, Megafon, Tele2 - annually spend more than 70 billion rubles on the lease of BS sites alone, not to mention the budget for BS maintenance, purchase and installation of related equipment. Another important factor is that technologies regularly change, are updated and improved, and therefore infrastructure ownership also forces you to pay attention to changes and respond accordingly. Therefore, in the field of communications and telecommunications, the scenario of fully virtualized networks is considered.

To calculate the cost of servicing such a network, the formulas from clause 3.4 are used, corresponding to the case with the lease of all equipment from the operator-owner. The parameters used in the calculations, as well as the estimated cost, are shown table 3. Figure 3 shows the results of the calculations.

Table 3. The main parameters used in the calculations.

Parameter	Value
Number of subscribers, thousands	10, 50, 100
Purchase cost of 1 gigabyte from the operator, USD	0.01
Annual traffic per subscriber, GB	15 GB*12 months

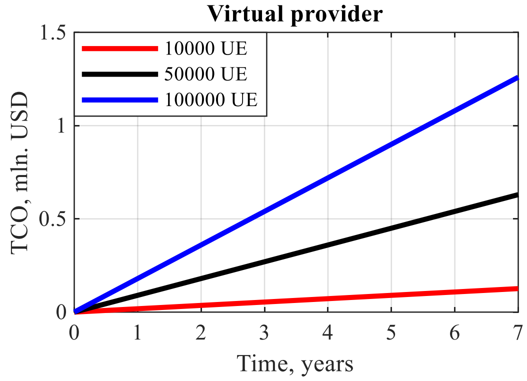

Figure 3. TCO of the virtual operator network (scenario 4)

4.2 Production and distribution of electricity

The energy industry is undoubtedly one of the most significant precedents for the use of 5G technologies due to the huge number of diverse requirements (Leligou H. C. et al., 2018).

Failures in electrical networks lead to significant costs for society. The causes of failures can be many factors: weather conditions, damage during excavation, equipment problems. However, some of these problems occur due to insufficient information about the state of network components.

Typically, distribution system operators want to own critical parts of the communications infrastructure for performance reasons as well as to better comply with regulatory requirements (Study of 5G as enabler of New Power Grid Architectures, 2022).

Therefore, operators are reluctant to place critical communication services on public networks and prefer to invest in their own infrastructure. And while owning the communications infrastructure makes it easier to control, in the long run it will be less cost effective than using the services offered by the provider. Therefore, as an alternative to full ownership of the 5G network, a more efficient option is to rent the core of the network and own only the network elements that are located on the sites. This also makes sense due to the lack of operator infrastructure in those locations where the presence of such infrastructure is necessary. Ownership of base stations provides a sufficient degree of confidentiality and performance, and also makes it possible to place base stations in the most suitable places for the operator. Thus, in the field of production and distribution of electricity, scenarios of a completely private network and a network with a leased core are suitable, which corresponds to the listed scenarios 1 and 2 from paragraph 3.

The calculation of the cost of ownership for the selected scenario is carried out according to the formulas from paragraphs 3.1 and 3.2. As initial parameters for this scenario, it is proposed to set the length of the power supply line (L) and the coverage radius of the base station (R). In such case, the formula for calculating the cost of an optical line takes the following form:

$$C_{optic} = L\left(C_{dig} + C_{rol}\right) \quad . (42)$$

The number of base stations depends on the length of the power line and the range of the base station, rounded up:

$$N_{site} = \frac{L}{2R} \quad . (43)$$

Taking into account all the above parameters for a power transmission line with a length of 1000 km and a BS coverage radius of 5 km (100 base stations), the cost of service has the following form, shown in Figure 4.

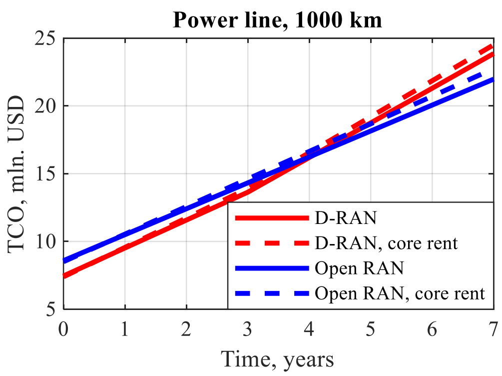

Figure 4. TCO energy industry, 1000 km

Figures 5-21 (See appendix) show the results of the capital and operating cost calculations in each case. The following symbols are used in the figures:

CR - core rent ; RU - RU Equipment, DU - DU Equipment, CU - CU Equipment, DU CU - DU CU Equipment, MAST - Base Station Mast, COOL - Cooling Plant, FRONTHAUL - Cost of Interface Boards, CW - Commissioning, OPTIC - Cabling, CORE – 5G core, DPC BUILDING – data processing center construction, SOFT – software, RU POWER – energy consumption costs RU, DU POWER – energy consumption costs DU, CU POWER – energy consumption costs CU, DU CU POWER – energy consumption costs DU CU, GROUND RENT - site rent, CORE POWER - core power consumption cost, COOL POWER - cooling plant power consumption cost, OEM - maintenance and operation, WAGES - employee wages, SOFT UPDATE - software update cost, OPTIC MAINTENANCE - optical cable maintenance.

The cost of core hardware is less than one percent, so in the case of a core lease (scenario 2), the picture will not change much.

Here the network core cost also takes up less than a percent, so in Scenario 2, the result will be identical.

4.3 Construction

Construction is a very dynamic environment in the sense that many different building infrastructure elements are in constant motion, such as builders, machinery and equipment. It is difficult to provide convenient and reliable wired communications in such a situation due to the fact that they cannot quickly adapt to changes and do not provide user mobility, and therefore wireless communication is a key element in providing communication on a construction site. For a housing construction enterprise, both a private network and a partial lease network can be considered. A full lease scenario is not recommended in this case, since construction sites are often located outside urban areas and do not always have simultaneous access to base stations and the network core. For this reason, the calculation of the cost of ownership of a network for housing construction can be carried out according to the formulas of paragraphs 3.1, 3.2 and 3.3. However, in this case, it is more expedient to consider the length of the optical line in the following form:

$$L_{optic} = 3R + \left(N_{site} - 3\right) \cdot 2R, \quad . (44)$$

since in order to reduce the length of optical lines, the DPC should be located at a minimum distance from the three nearest base stations. In this scenario, the coverage area is well localized around construction sites. The following figures show the results of estimating the cost of maintaining the network of a construction enterprise.

As can be seen from the figures, for all scenarios, Open RAN requires more investment at the start, but over a seven-year period it becomes more profitable than D-RAN. This is because maintenance and operation costs, as well as software upgrades, are much higher in D-RAN, so operating costs rise faster over time.

Most of the capital expenditures in the energy and residential sectors are occupied by the laying of optical cable: 46%-54% for D-RAN and 50%-54% for Open RAN. Operating expenses in D-RAN largely depend on RU power consumption, site rent, maintenance and software updates, while in Open RAN the vast majority of costs fall on RU power consumption and site rent. The cost of renting a core slightly increases operating costs, and with them TCO.

In the site lease scenario, 90% of the capital expenditures are for the construction of the data center and core hardware. In this case, the cost of renting sites is 83% of all operating expenses.

As for the virtual operator, the cost of such a network is completely dependent on the operator and increases linearly with the increase in the number of subscribers, if the tariff does not provide for flexible pricing.

5. CONCLUSION

The paper defines the concepts of capital and operating costs in the deployment and maintenance of the network and the total cost of the network, and also describes the network architectures of D-RAN, C-RAN and Open RAN. A detailed description of four scenarios for deploying a 5G network with different distribution of network components is presented, indicating the advantages and disadvantages. For each scenario, a calculation of capital and operating costs for network deployment and maintenance is presented. Calculations were performed for three areas: virtual telecom operator, electricity generation and distribution, and housing construction. In each case, the rationale for choosing the calculation method depending on the scenario is given, as well as all the results obtained and their analysis are shown.

The virtual operator network can be built on the leased equipment of both the network core and base stations. The deployment and maintenance costs in this case are completely determined by the billing of the lessor company. In the field of power generation and distribution, Open RAN appears to be a more advantageous architecture in the long run. In the housing sector, the scenario with the lease of base stations and a private core turns out to be the most profitable option.

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Danila Kondrashov
Tomsk State University of Control Systems and Radioelectronics,
Tomsk,
Russia
danila.a.kondrashov@tusur.ru
ORCID 0000-0001-5042-9372

Evgeniy Rogozhnikov
Tomsk State University of Control Systems and Radioelectronics,
Tomsk,
Russia
evgenii.v.rogozhnikov@tusur.ru
ORCID 0000-0001-7599-0393

Renat Abenov
Tomsk State University of Control Systems and Radioelectronics,
Tomsk,
Russia
abenov.rr@gmail.com
ORCID 0000-0002-6688-289X

Serafim Novichkov
Skolkovo Institute of Science and Technology,
Moscow,
Russia
s.novichkov@skoltech.ru
ORCID 0000-0001-9019-6956

Evgeniy Ageev
Tomsk State University of Control Systems and Radioelectronics,
Tomsk,
Russia
eugene.ageyev@gmail.com
ORCID 0000-0002-6813-1977

Andrey Zhalsaraev
Tomsk State University of Control Systems and Radioelectronics,
Tomsk,
Russia
andreika3981@gmail.com
ORCID 0000-0002-1208-4382

APPENDIX:

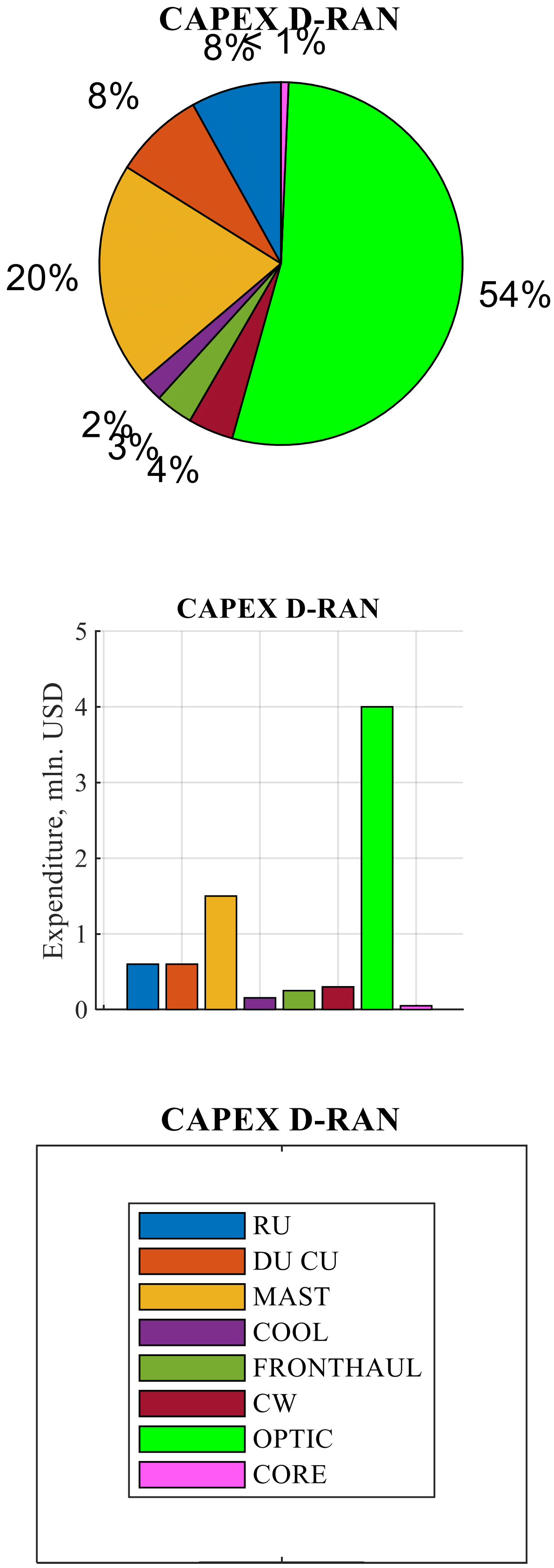

Figure 5. Composition of D-RAN capital costs (scenario 1, 1000 km)

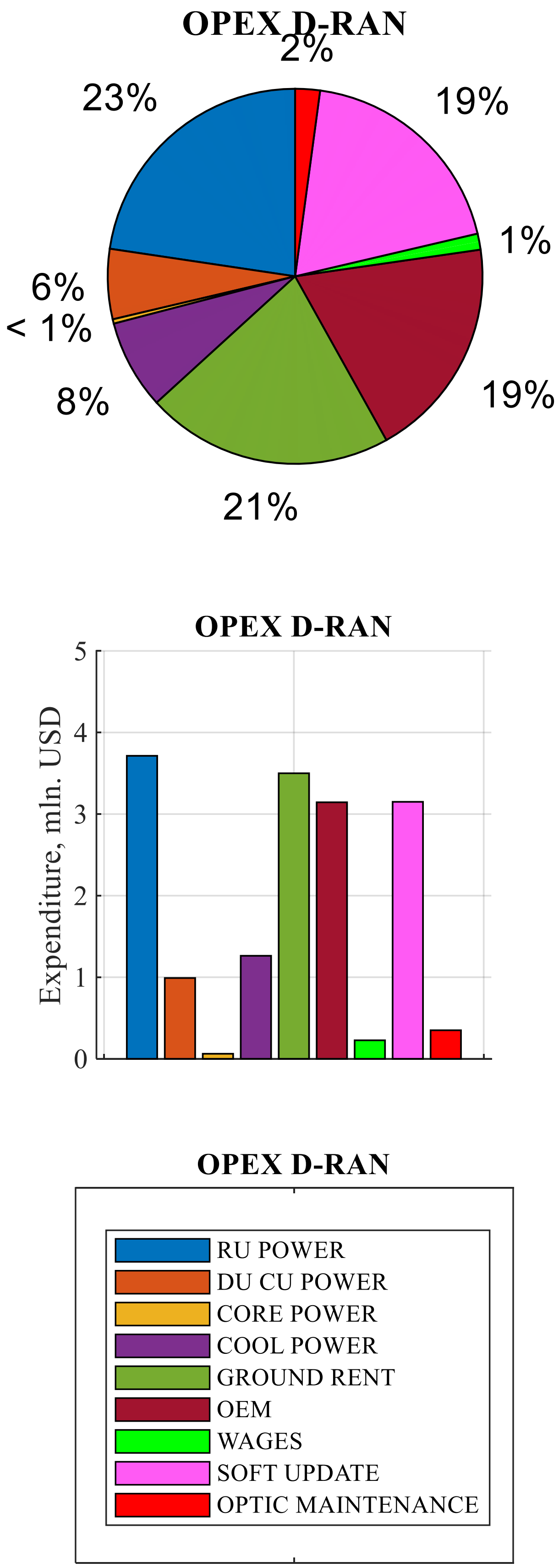

Figure 6. Composition of D-RAN operating costs (scenario 1, 1000 km)

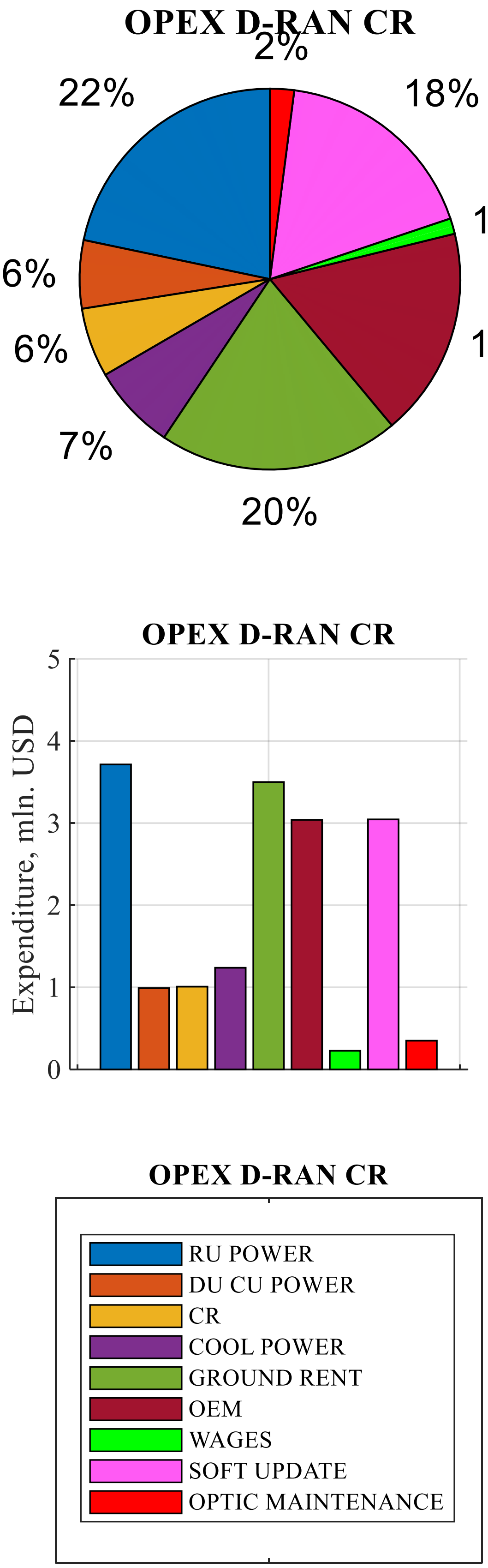

Figure 7. Composition of D-RAN operating costs (scenario 2, 1000 km).

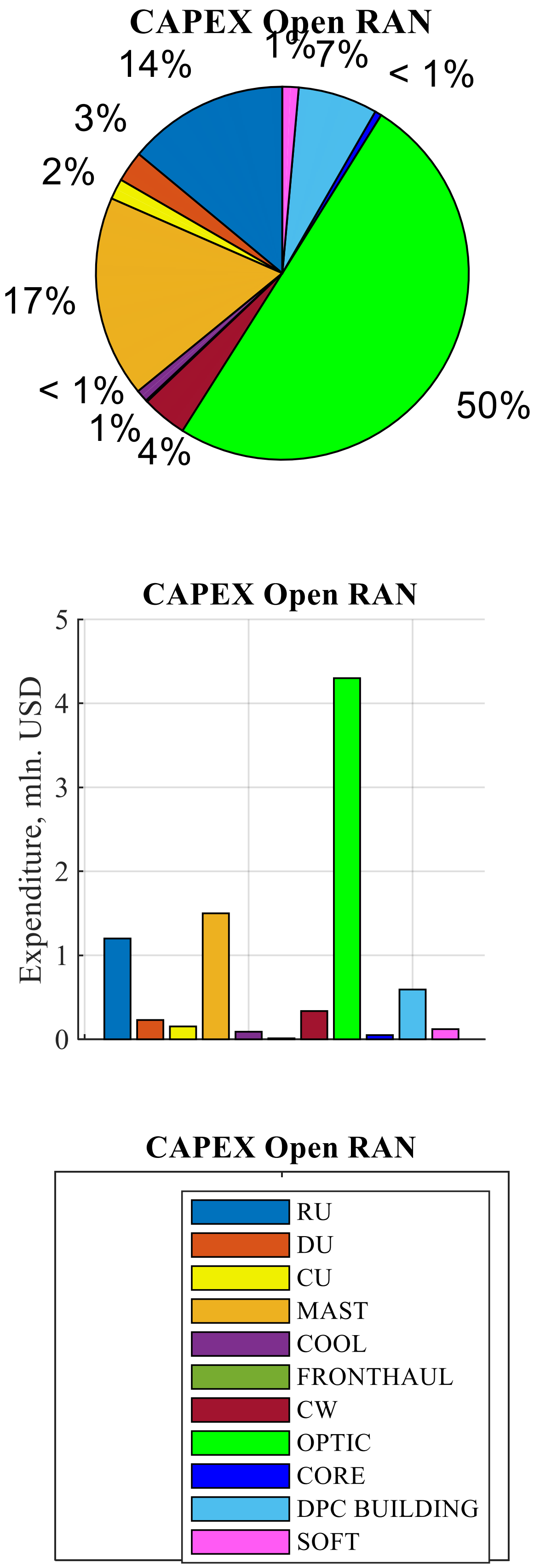

Figure 8. The composition of the capital costs of Open RAN (scenario 1, 1000 km)

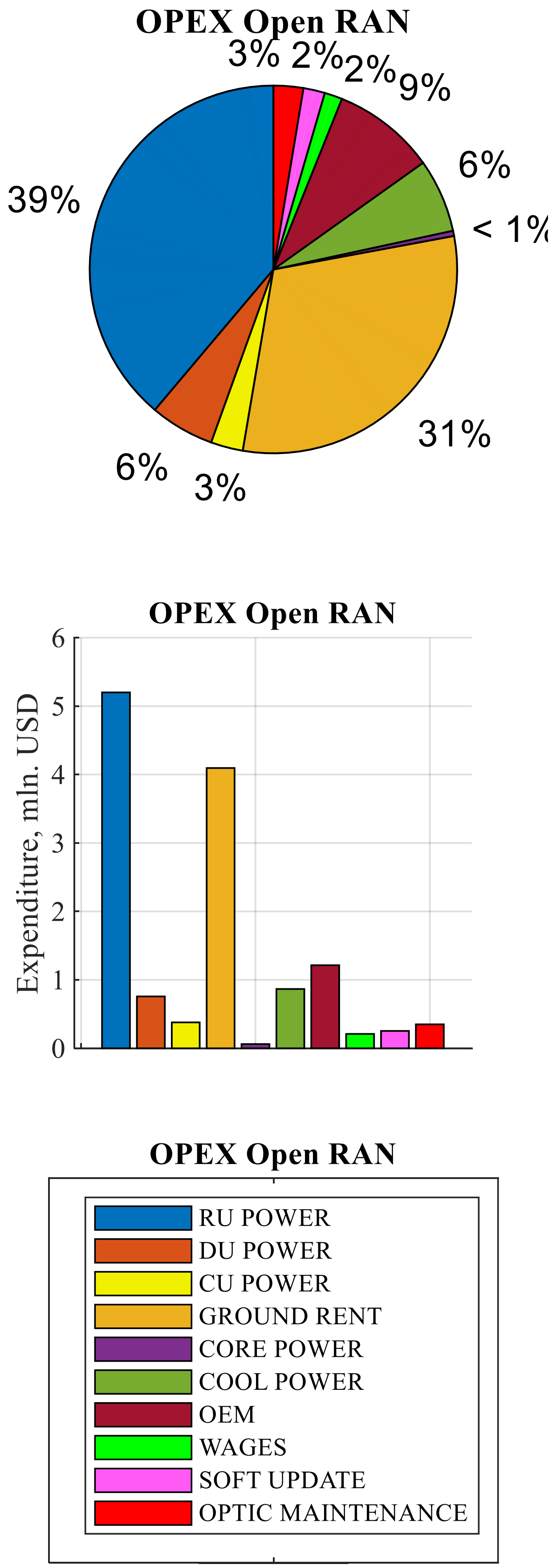

Figure 9. The composition of the operating costs of Open RAN (scenario 1, 1000 km)

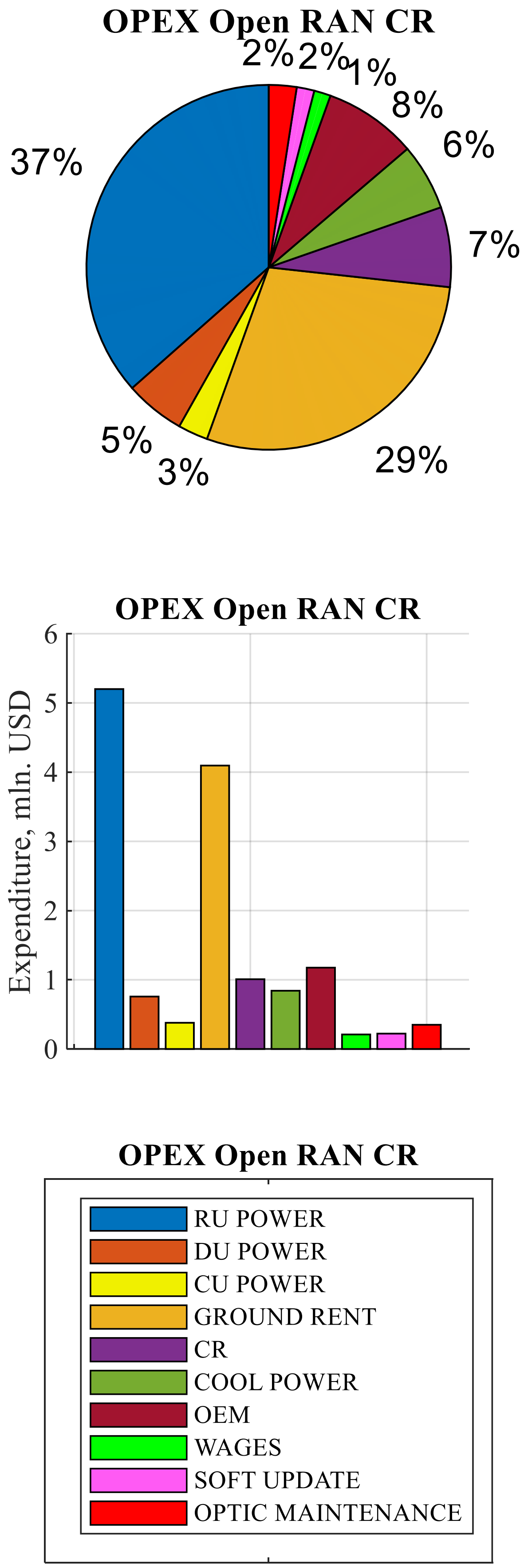

Figure 10. The composition of the operating costs of Open RAN (scenario 2, 1000 km)

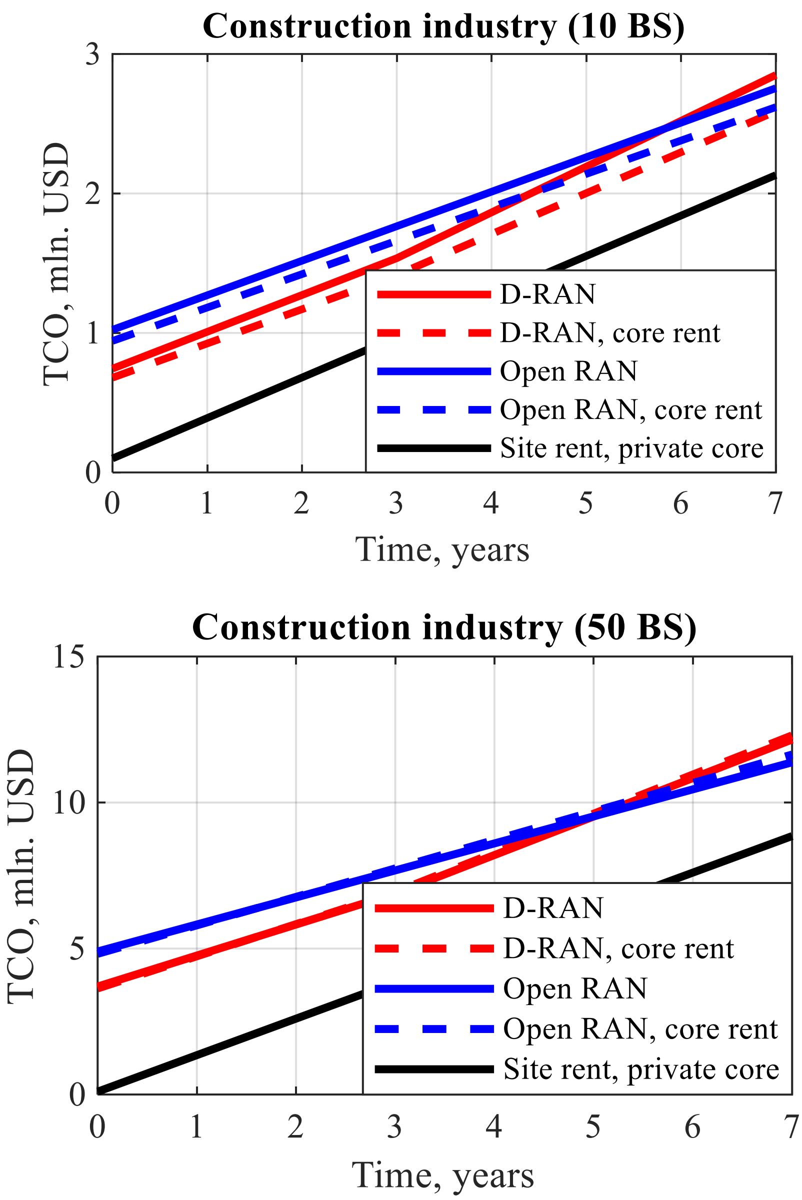

Figure 11. TCO for 10 and 50 BS.

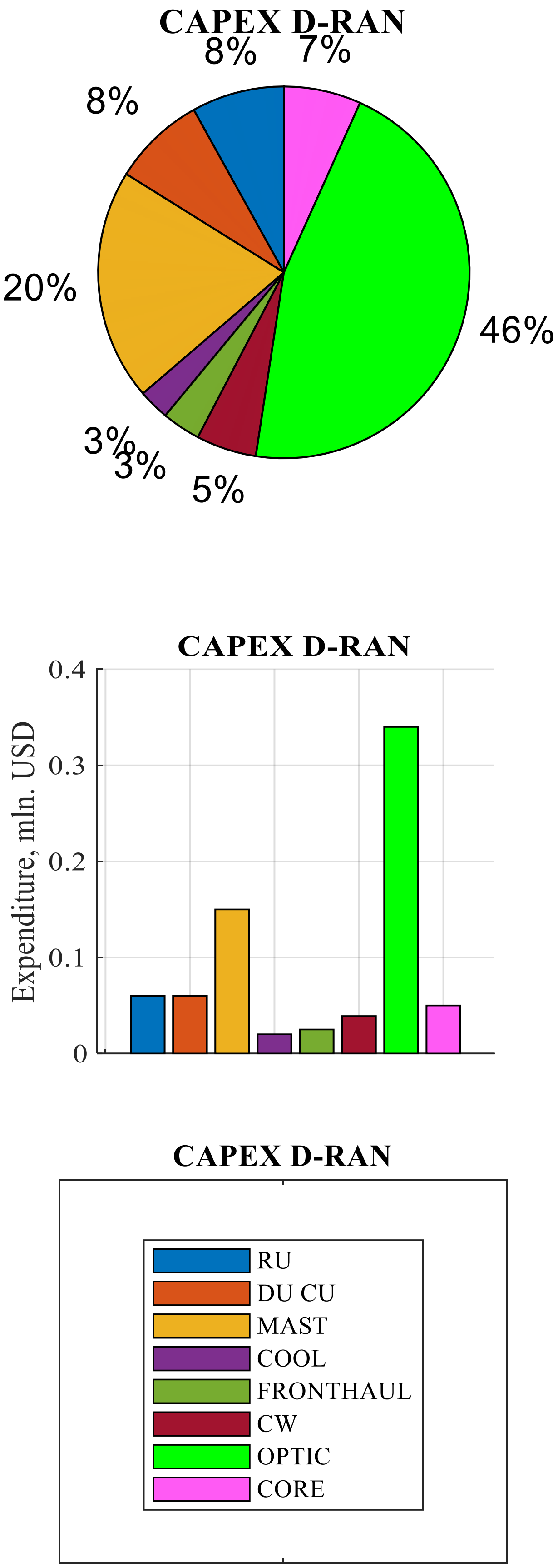

Figure 12. Composition of D-RAN capital costs (scenario 1, 10 BS)

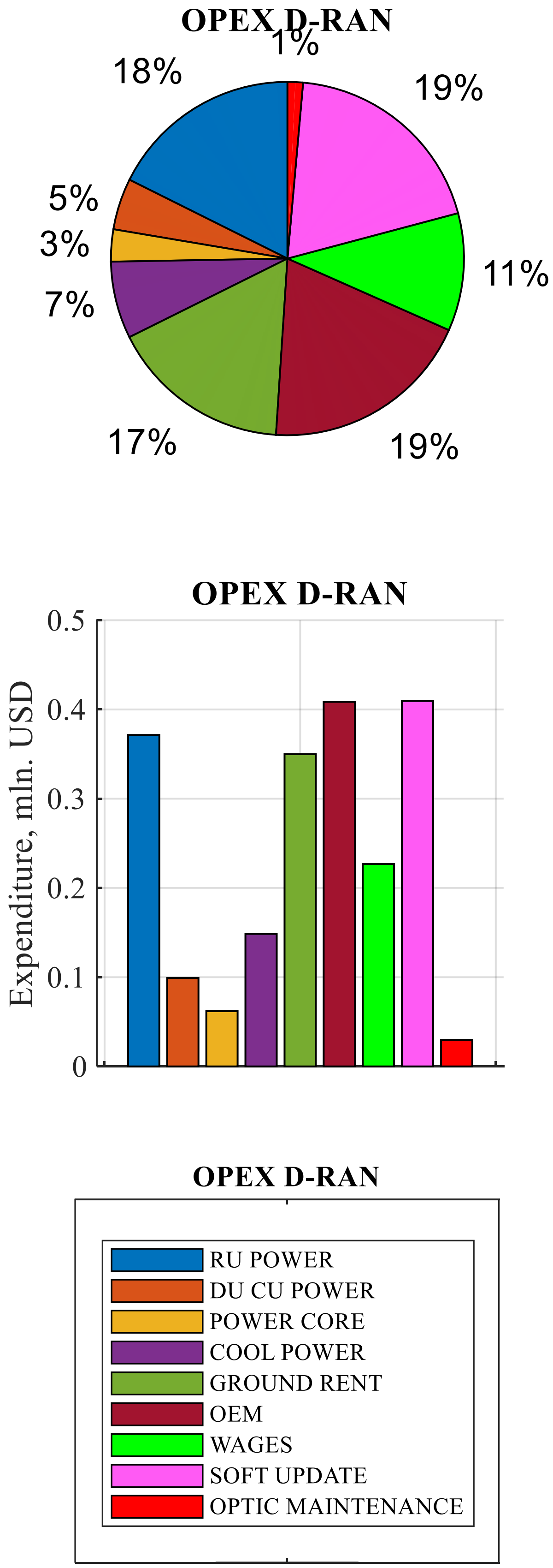

Figure 13. Composition of D-RAN operating costs (scenario 1, 10 BS)

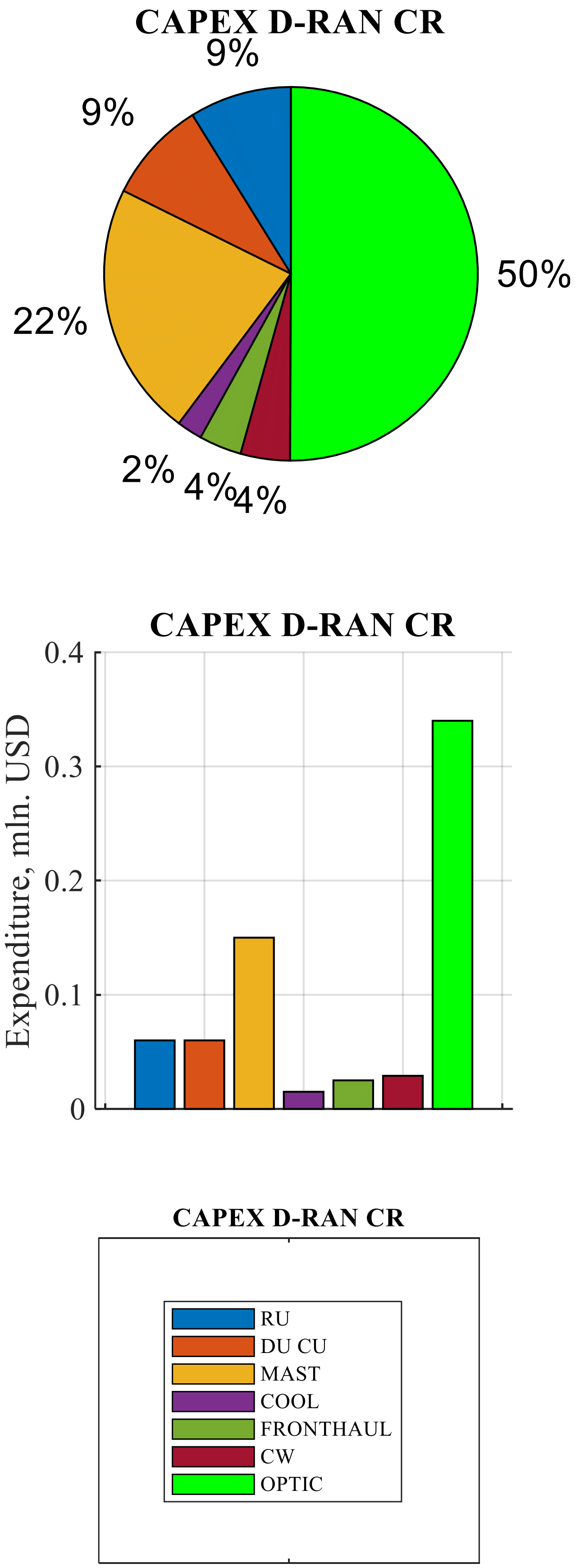

Figure 14. Composition of D-RAN capital costs (scenario 2, 10 BS)

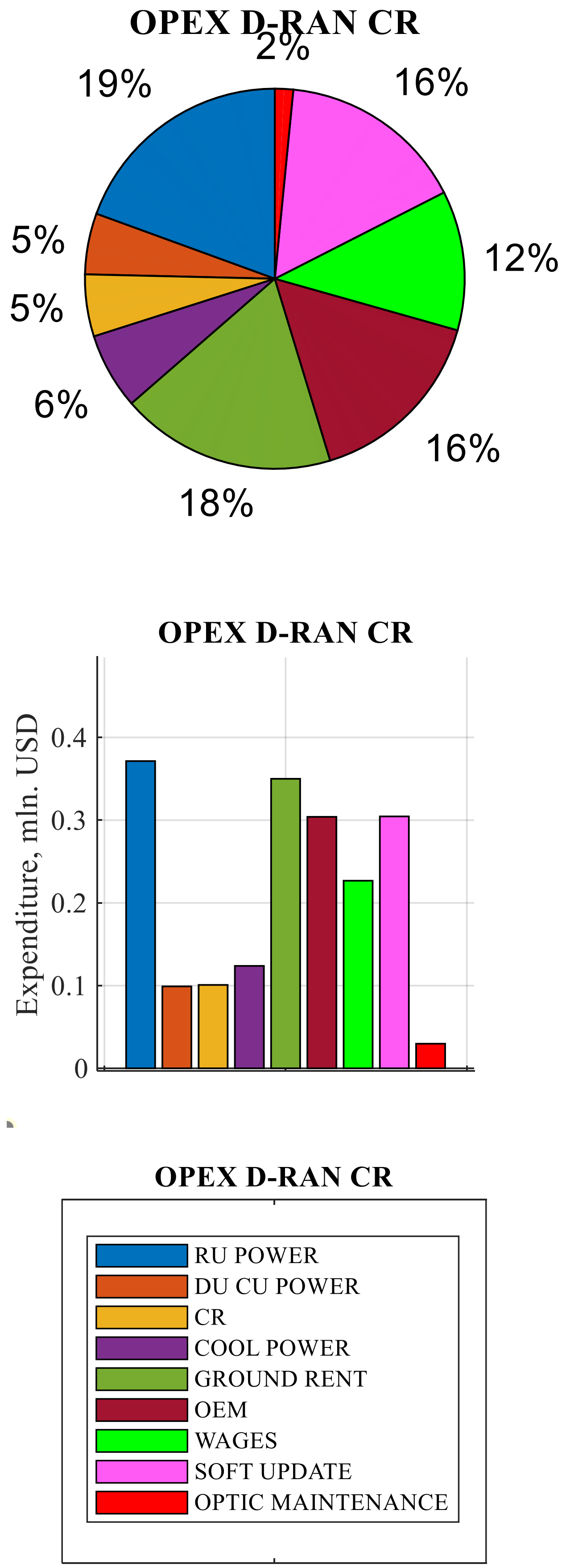

Figure 15. Composition of D-RAN operating costs (scenario 2, 10 BS)

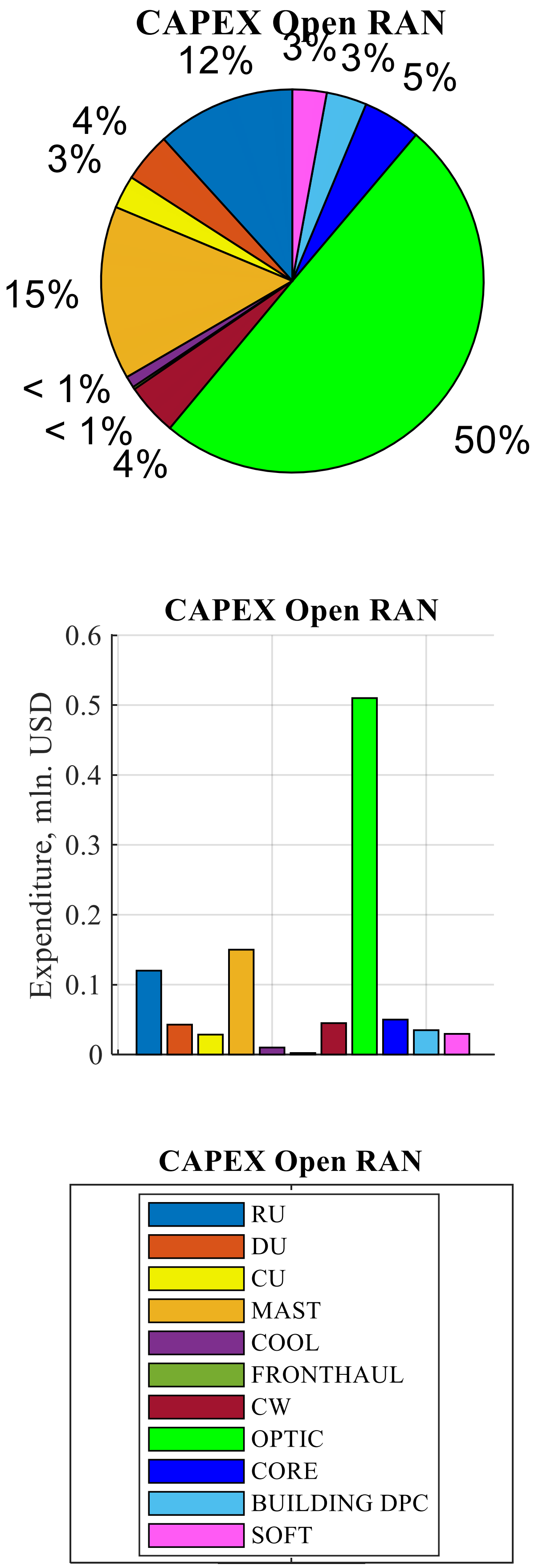

Figure 16. The composition of the capital costs of Open RAN (scenario 1, 10 BS)

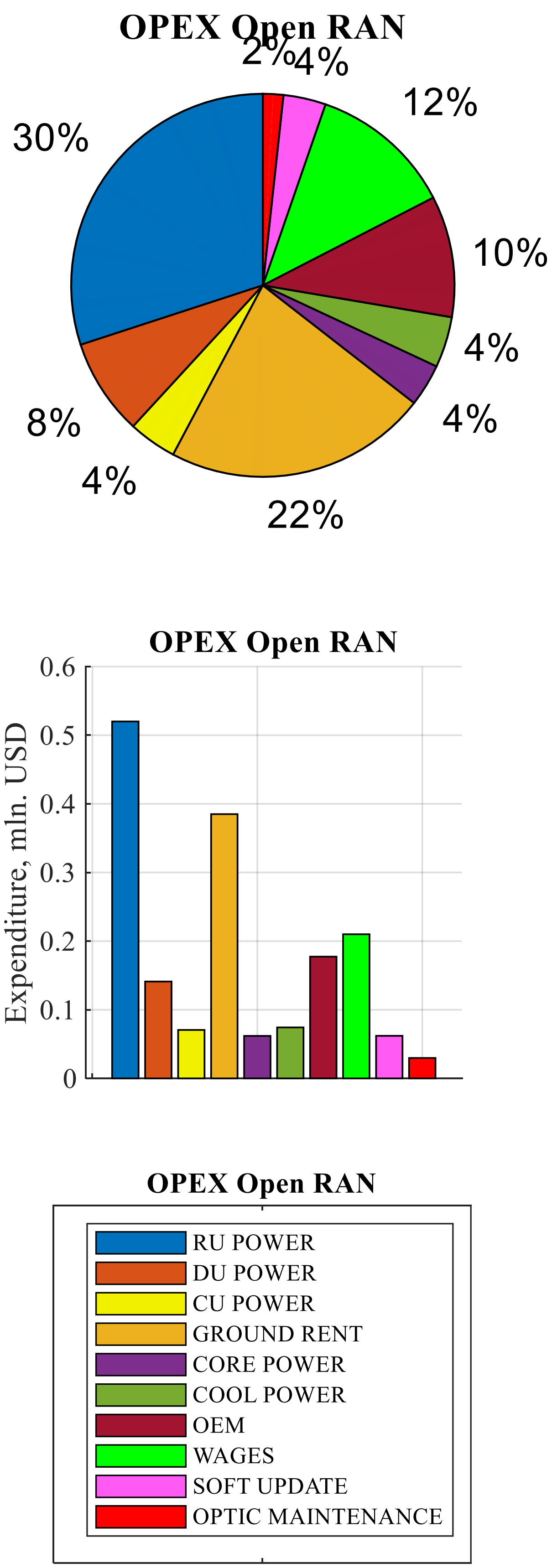

Figure 17. The composition of the operating costs of Open RAN (scenario 1, 10 BS)

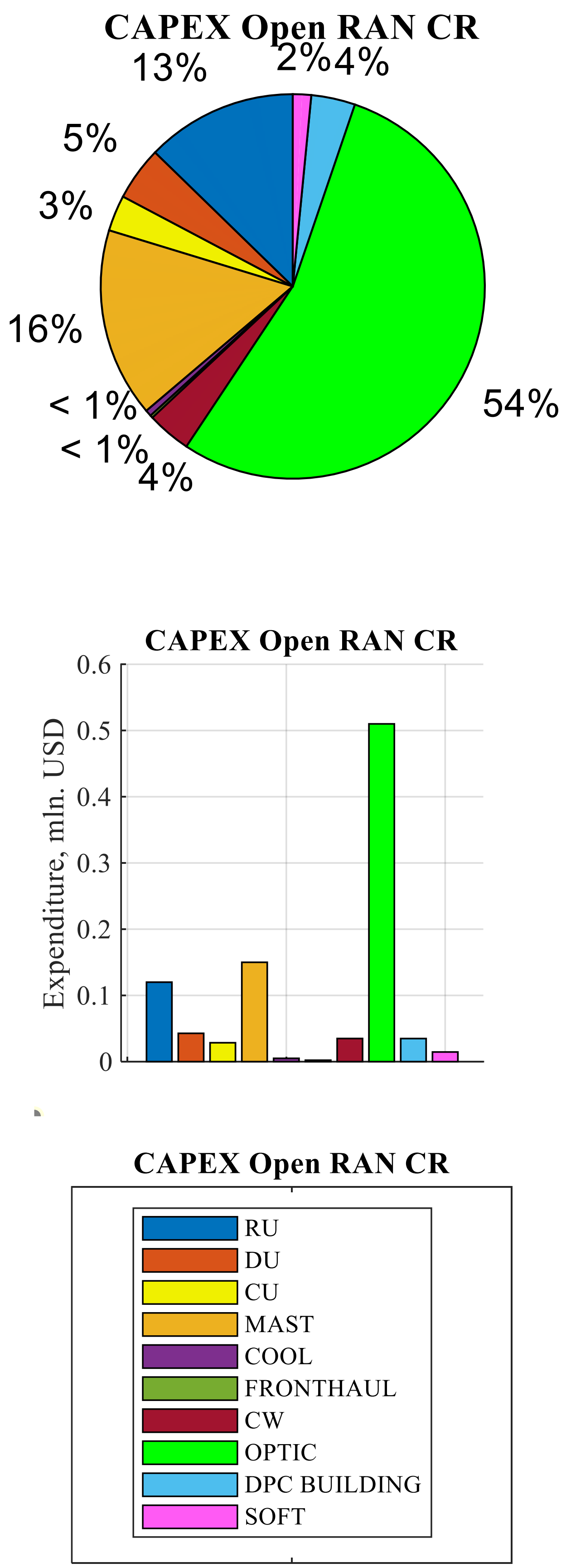

Figure 18. Composition of capital costs of Open RAN (scenario 2, 10 BS)

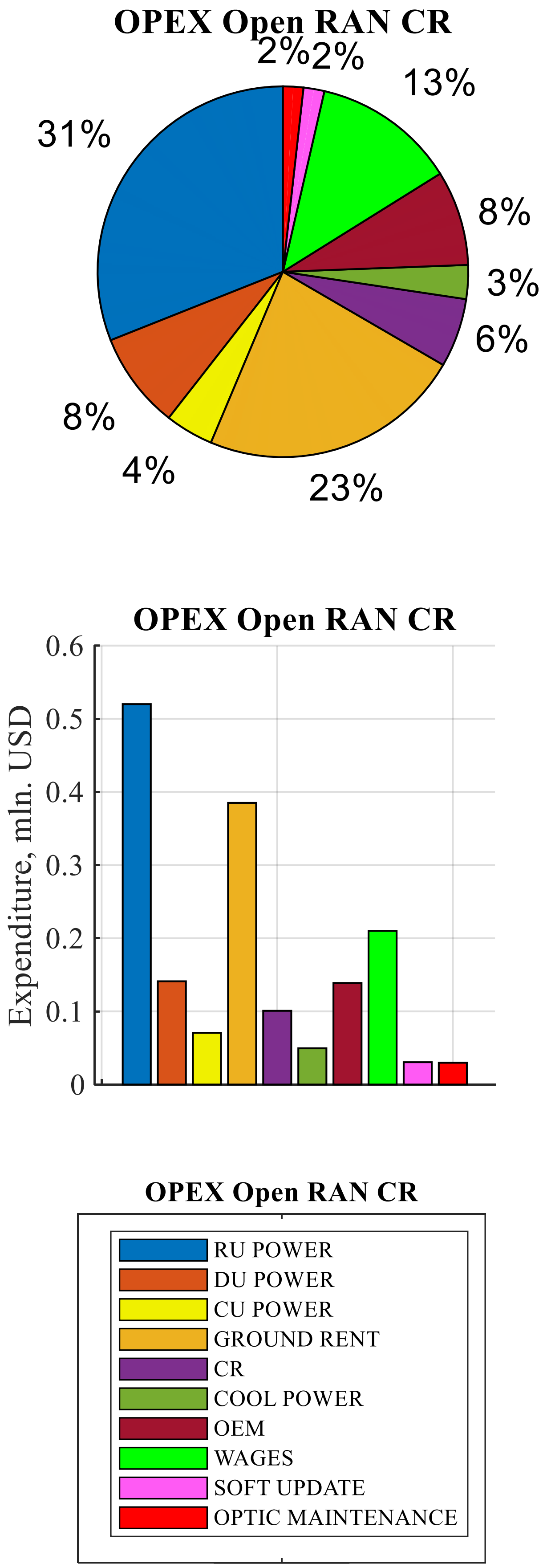

Figure 19. The composition of the operating costs of Open RAN (scenario 2, 10 BS)

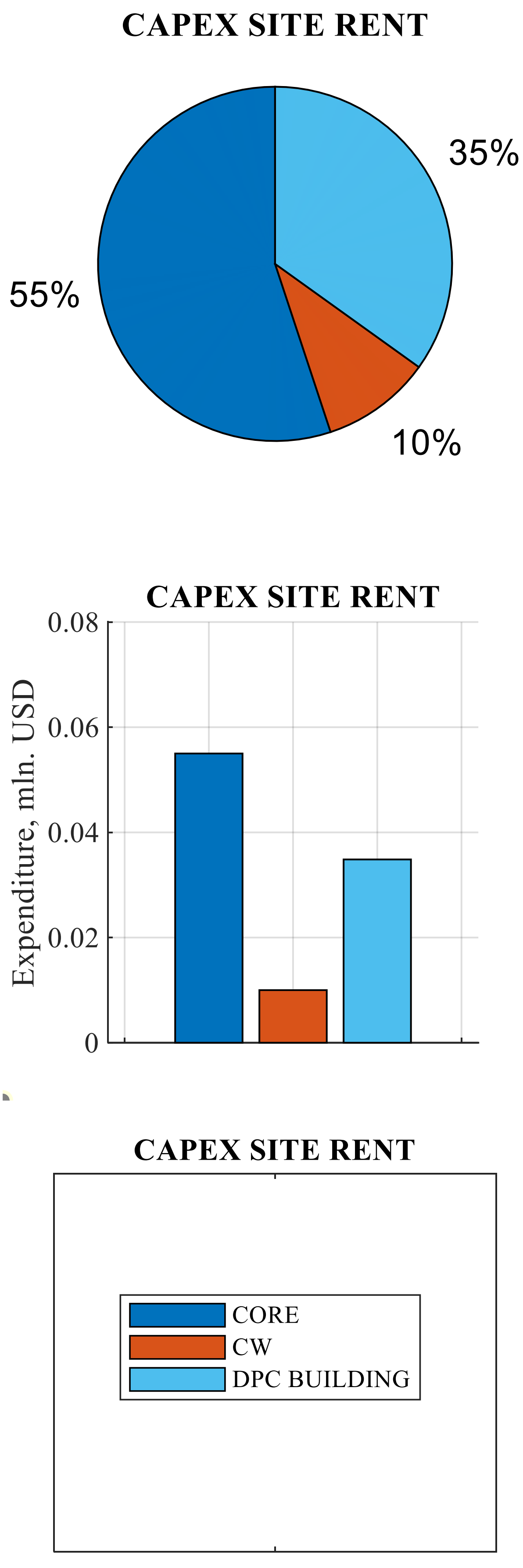

Figure 20. Composition of capital costs (scenario 3)

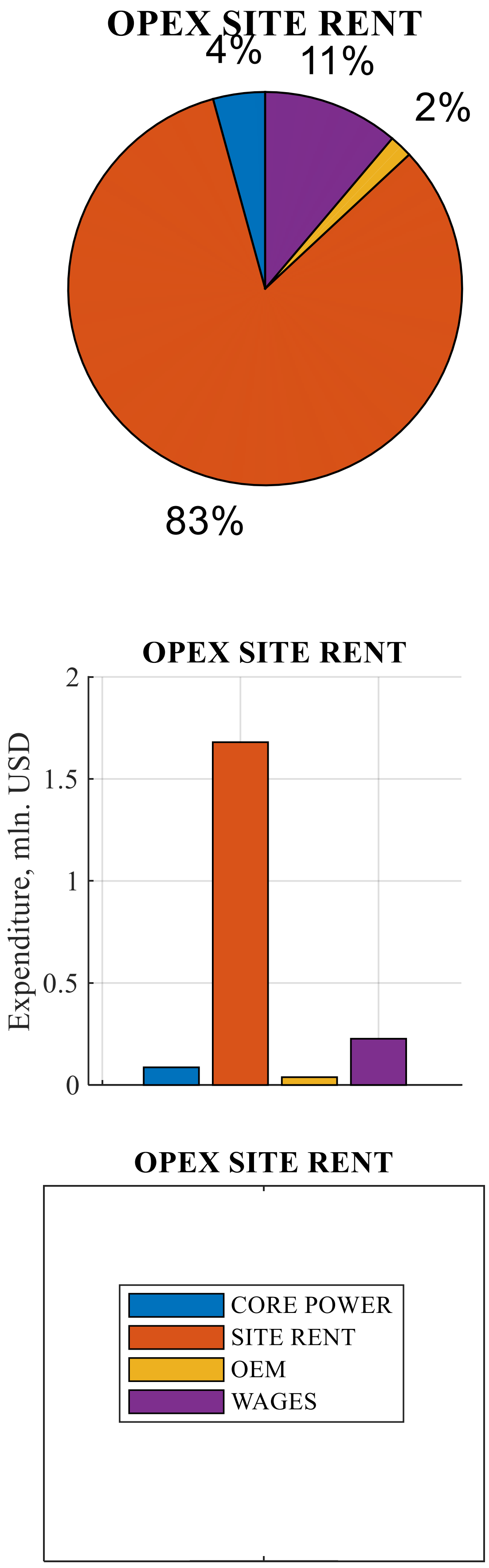

Figure 21. Composition of operating costs (scenario 3)