“Techno-economic assessment studies”

D5.3

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Abstract:
This deliverable provides an overview of the cost assessment performed for the Next Generation Optical Access Networks proposed in the OASE project. The cost assessment includes both Capital and Operational expenditures of different implementation scenarios (from greenfield to migration; with and without node consolidation; with and without protection). The cost assessment could be used as a basis by operators by using the scenario most suitable to their case study. Furthermore, the key cost factors have been identified based on the cost assessment and a detailed sensitivity analysis and gives important feedback to operators and manufacturers on which parameters should be carefully considered when planning networks and developing components.

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Table of Contents

Executive summary

One of the objectives of the OASE project is to propose architectures able to guarantee the requirements for next generation optical access networks. However, operators and manufacturers are interested to evaluate the cost of each architecture in different scenarios and to identify the cost drivers and key cost parameters.

Traditional optical access networks have been modelled based on the household concentration of each area, which were classified as rural, urban and dense urban. However, operators are playing with the possibility to change the scenario and reduce the number of central offices, aiming at reducing costs, but also increasing the distance to users significantly and changing the user distribution. The impact of the reduction of central offices, referred in this document as node consolidation has been evaluated.

The cost evaluation is based on the extended TONIC tool, which has been implemented within Task 5.2. The TONIC tool is able to dimension and evaluate cost of different architectures (GPON, XGPON, Hybrid PON, WS WDM PON, WR WDM PON, AON + WDM Backhaul) for different areas (dense urban, urban, rural) and different network consolidation scenarios (non-node consolidation, conservative node consolidation, and aggressive node consolidation). The dimensioning is done based on the selected penetration curve (chosen among 7), the PIP penetration curve (either Greenfield in 2010 or in 2020) and the assumed duct availability (5 available alternatives). The cost assessment comprises infrastructure and equipment cost evaluation as well as fault management, service provisioning, energy, floor space and maintenance required for each year based on the number of connected users. Moreover, the tool is able to distinguish physical infrastructure provider (PIP) costs from the network provider costs. The cost assessment considers the increase of salaries and energy cost per year and provides non-discounted and discounted costs.

The proposed architectures are compared from the cost point of view under different deployment assumptions:

- Migration from an existing traditional optical access network such as GPON or AON. In this migration scenario, the investments in terms of infrastructure and equipment are considered assuming an existing optical distribution network (ODN). This ODN can be used for the NGOA from the migration starting time on.

  The cost assessment shows that for all the architectures have higher OPEX than CAPEX costs when summing the costs from 2020 to 2030 (NGOA operational time) for any type of area (i.e. DU, U and R). The most costly architecture is the UDWDM for any area, whereas the less costly solutions is to keep existing optical access networks: upgrade existing GPON by reducing the splitting ration from 32 to 8 so that the bandwidth increases or to keep the AON as it is. The CAPEX key cost factors of these architectures differ: for UDWDM is NP and CPE equipment, for AON is the NP equipment and in-house infrastructure, whereas for the GPON upgrade is CPE and in-house infrastructure. Regarding OPEX, the most important factor is the service provisioning. The impact of energy and FM differs significantly on the architecture (e.g. UDWDM has high energy and FM but relatively low CPE energy cost; AON has

low CPE related costs; whereas GPON has lower values but slightly higher CPE energy cost).

When considering node consolidation, more architectures have been evaluated since they can offer the long reach requirements while keeping the high bandwidth per user. In this scenario, it can be observed that the upgrade of GPON by reducing the splitting ratio is not an option due to the high costs related to the new LL5 links (increases more than 1 CU/year per user). Some architectures keep and even decrease their average TCO per user per year when applied to aggressive node consolidation scenarios: e.g. HPON40 (for any area) and WSWDM PON (for DU) solutions. Furthermore, the options to connect AON AS with a WDM Backhaul, or migrate from GPON to HPON architecture are the most effective solutions for any type of area applying node consolidation.

- Migration from a non-optical access network towards an NGOA. This migration scenario considers a network provider greenfield scenario where some ducts can be used to install the optical fiber. The impact of an NP greenfield is mostly on the increase of service provisioning costs due to the higher effort required to connect all users, as well as on the infrastructure cost (especially in rural areas where the distances are significantly longer).
- The impact of the ducts availability on the total cost is given by comparing the previous results with a pure greenfield scenario as well as with a higher availability scenario. The impact of duct availability on the infrastructure cost differs on the architecture and on the area: higher for DU than rural areas, higher for AON P2P and WRWDM PON than HPON solutions.
- A higher fanout will for all architectures lead to a lower cost per home passed and to a lower overall cost. Cost reductions up to 30% and more are reachable by increasing the fanout substantially. It should be noted that the higher fanout cases might conflict with the consolidation possibilities – as a higher fanout will reduce the reach – and maximum dedicated bandwidth – as with a higher fanout, more customers are sharing the same OLT port. Relaxing the OASE requirements – for instance only in an initial phase – could as such reduce the upfront costs substantially
- Regional differences could lead to a very different cost of deployment. Especially in those European countries with lower average salaries, the costs could be much lower. Next to the salary, the adoption is the most important impacting factor and a higher adoption will lead to a lower cost per customer in the end.
- The impact of costs of the ONT and OLT equipment behaves more or less linear for all architectures and has a rather limited impact up to resp. ~5% or ~2% for an increase up to 50% of its original cost.
- Adoption has most probably the highest impact of all factors and has been split into initial adoption effect (e.g. by means of presubscriptions) and the steepness of the adoption curve. Increases in the initial adoption lead to the most substantial decrease in the cost per subscription year. Still the effect of having a faster adoption is certainly very important

Referred documents

[1] OASE Deliverable D2.2 “Consolidated requirements for European next-generation optical access networks” June 2012
[2] OASE Deliverable D5.2 “Process modeling and first version of TCO evaluation tool” December 2011
[3] OASE Deliverable D5.1 “Overview of Methods and Tools” October 2010.
[4] OASE Deliverable D6.3 “Value network evaluation” December 2012
[5] OASE Deliverable D3.2 “Description and assessment of the architecture options” September 2012
[6] OASE Deliverable D4.2.2 “Technical assessment and comparison of next-generation optical access system concepts” March 2012
[7] OASE Deliverable D6.2 “Market Demands and Revenues” June 2012.

List of figures and tables

Abbreviations

AON	Active Optical Network
APD	Avalanche Photodiode
ARN	Active Remote Node
AS	Active Star
AWG	Array Waveguide Grating
BF	Brownfield
CAN	Central Access Node
CAPEX	Capital Expenditures
CD	Cumulative Discounted
CO	Central Office
CPE	Customer Premises Equipment
CRF	Constant Revenue Flows
CU	Cost Unit
DF	Distribution Fibre
DU	Dense Urban area
DWDM	Dense WDM
E2E	End to End
EDFA	Erbium doped fiber amplifier
FF	Feeder Fibre
FIT	Failures in Time
FTTH	Fibre To The Home
FTTx	Fibre To The X
FM	Fault Management
GF	Greenfield
GPON	Gigabit Passive Optical Network
HC	Homes Connected
HH	Households
HPON	Hybrid Passive Optical Network
HVAC	Heating, Ventilation, and Air Conditioning
IT	Information Technology
LEx	Local Exchange
LT	Line Termination
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NGOA	Next Generation Optical Access
NMS	Network Management System
NP	Network Provider
NPV	Net Present Value
ODN	Optical Distribution Network
OEO	Optical to Electronic to Optical conversion
OLT	Optical Line Terminator
ONT	Optical Network Terminal
ONU	Optical Network Unit
OPEX	Operational Expenditures
p2p	Point to point
PCP	Physical Connection Point
PIN	p-i-n diode

PIP	Physical Infrastructure Provider
PON	Passive Optical Network
PS-PON	Power Splitting PON
PUE	Power Usage Efficiency
pWDM	Passive WDM
QoS	Quality of Service
R	Rural area
RE	Reach Extender
RN	Remote Node
SME	Small and Medium-sized Enterprises
SP	Service Provisioning
TCO	Total Cost of Ownership
TDM	Time Division Multiplexing
TONIC	Techno-Economics of IP Optimized Networks and Services
TRX	Transmitter
U	Urban area
UDWDM	Ultra Dense WDM
UPS	Uninterruptable Power Supply
WACC	Weighted Average Cost of Capital
WDM	Wavelength Division Multiplexing
WS WDM PON	Wavelength Selective WDM PON
WR WDM PON	Wavelength Routed WDM PON
XGPON	10G PON

1. Introduction

One of the main objectives of the techno-economic assessment of the different architectures on the different scenarios is the validation of the requirements defined in WP2 from the economic point of view [1]. Furthermore, this document also presents the impact of different parameter ranges on the total cost, based on sensitivity studies, to give guidelines for overall TCO reduction. WP5 does not impose or revise requirements from a technical perspective. Figure 1 gives an overview about the required input data for the TCO evaluation and the refinement loop between the techno-economical results and the NGOA requirements.

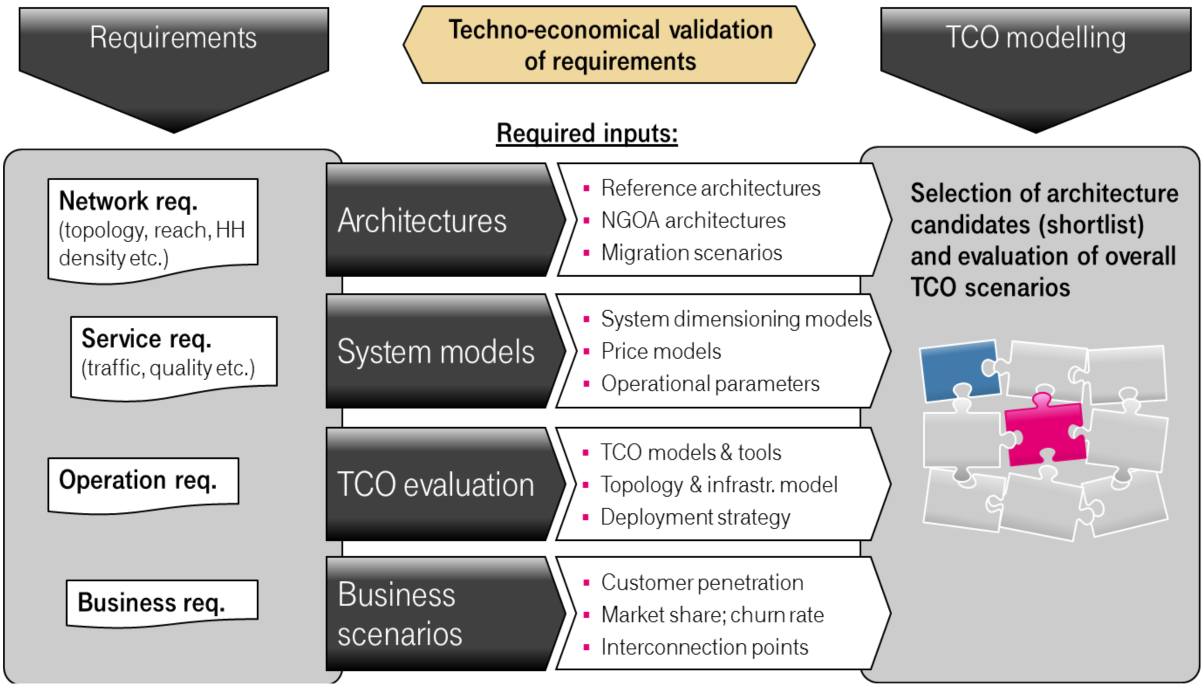


Figure 1 Overview of the required TCO input data

The aim of the techno-economical assessment is the revision of the NGOA requirements and a comparison with the reference architectures. For this, NGOA network scenarios have been developed considering, for example, geographic coverage of access areas, network topology, geographical distribution of customers and traffic demand, future traffic growth, service penetration evolution etc. General TCO evaluations of NGOA network architecture scenarios will be performed, using the tools and cost models developed in tasks T5.1 and T5.2. It includes CAPEX for systems and infrastructure, OPEX for service provisioning, fault management, maintenance and power consumption as well as migration specific expenditures. The document presents the cost analysis performed for different migration cases, architectures and scenarios.

The cost assessment presented in this document covers the following studies:

- Migration cost evaluation from existing traditional optical access solutions to Next Generation Access networks, which is referred in this document as "**Migration: NP Brownfield**" studies. In this case, infrastructure and equipment exists for the non-node consolidation scenario when having GPON, AON or other traditional optical access networks. This study evaluates the increase of costs to migrate to NGOA solutions when keeping non-node consolidation or when considering aggressive node consolidation. This study is presented in Section 4.1.

- Migration cost evaluation from non-optical access networks (e.g. copper network) where some ducts may be available to be used by optical cables. This case is referred as "**NP Greenfield**" and is presented in Section 4.2.
- Furthermore, it may require the cost evaluation from a **pure Greenfield** scenario, that is, no NP or PIP available. The cost difference of this solution versus the "NP Greenfield" is presented in Section 4.3.

The impact of some aspects such as migration duration, protection, and migration starting time, is also stated. Furthermore a complete sensitivity analysis showing the impact that the variation of some parameters (due to regional location, time dependence or wrong estimations) have on the cost assessment is also provided in this deliverable.

The cost assessment also aims at identifying the key cost drivers and evaluating the impact that different input parameters and the targeted European region will have on the results.

The document is structured as follows: Section 1 provides a general description. In Section 2 the general cost model is described. Section 3 presents the case studies in terms of network scenarios (including type of area, node aggregation degree, penetration curves and duct availability), technologies, protection and open access. Section 4 presents the whole cost assessment for the different migration cases. In Section 5 some more specific cost studies are presented, which includes the impact of protection on the cost, cost evaluation of specific equipment required for the migration or the impact of the migration duration on the cost. Section 6 is devoted to all the sensitivity studies performed such as the impact that regional parameters have on the cost assessment. Finally Section 7 concludes the deliverable.

2. TCO Modelling

This section gives an overview of the relevant input parameters and boundary conditions of the study, comprising TCO building blocks, deployment conditions, demand scenario and aggregation cost model.

2.1. TCO building blocks

The TCO model comprises investments for all active and passive system and infrastructure components, expenditures for network operations and location infrastructure as well as migration related cost. Figure 2 shows the considered building blocks of the TCO model, which is based on the process modelling, proposed in D5.2 [2].

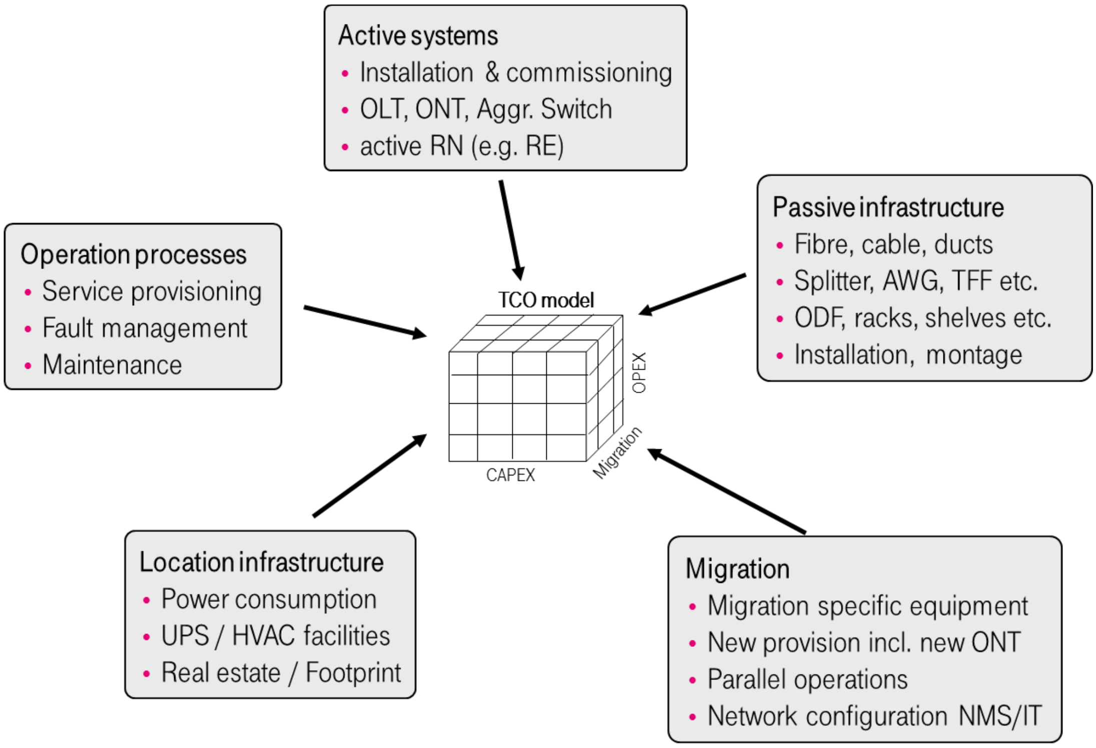


Figure 2 Building blocks of the TCO model

The business case has a time horizon for the NGOA deployment and operation from 2020-2030. For simplification, 100% of the FTTH network basic rollout has been considered in the first deployment year, even if this does probably not reflect the reality of what is likely to occur. No significant difference is expected for the system architecture comparison as compared to a delayed deployment, e.g. by over 3 years. In order to cover the varying infrastructure and topology requirements (e.g. available ducts, reach etc.) of different access areas, three Geo-type clusters: Dense Urban, Urban and Rural have been compared. The TCO modelling is performed for one typical/traditional service access area of each Geo-cluster. The passive fibre infrastructure deployment of the PIP takes into account existing free duct infrastructure (Brownfield), but no potentially existing spare fibres. For the NGOA system deployment of the NP, a Greenfield scenario in areas without existing FTTH and a migration scenario in areas with existing FTTH deployment (e.g. GPON or P2P) have been evaluated. In the migration scenarios, two FTTH initial architectures are considered from 2010-2019, in order to cover the upfront ODN deployment cost and to estimate the proper migration start point in 2019/20.

2.2. Demand scenario

Major drivers for optical network deployments are market demands and competition. The network design and dimensioning depends primary on the evolution forecast of service penetration and sustainable traffic per user as well as the requested access peak bandwidths. These dimensioning parameters are basically influenced by the offered service portfolio and competition situation in an access area.

Figure 3 shows an example penetration forecast for Germany for a time horizon till 2030, obtained from WP6. It reflects the average FTTH penetration of all deployed access areas. The migration strategy may depend on the reached penetration level in the migration start year (e.g. in 2020). In case of a relatively low customer penetration in 2020 on the existing FTTH platform, a "forced" migration with a completely switchover of all existing customers may come in the game instead of an "overlay" migration over several years in order to avoid parallel platform operations.

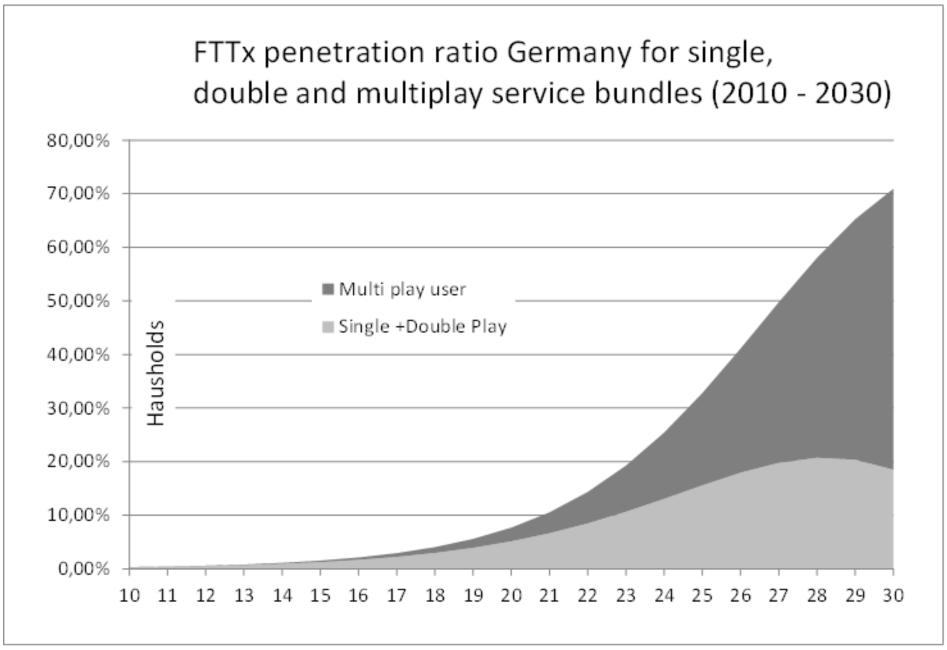


Figure 3 Penetration evolution

Figure 4 shows the WP2 requirement on the evolution of the sustainable traffic per customer. A Medium traffic case with 300 Mbit/s per customer (in 2030) has been considered out of the spanned traffic corridor for the TCO base scenarios. The sustainable traffic evolution is especially relevant for the aggregation and OLT switch dimensioning and in TDM based architectures also for the feeder dimensioning. The Max traffic case determines the system minimum requirement (i.e. NGOA systems have to support it) and will be considered as a sensitivity study.

Peak access bandwidths:

- Residential: 1G per ONT
- Business: 70% 1G and 30% 10G per ONT
- Mobile backhaul: 10G per Base station

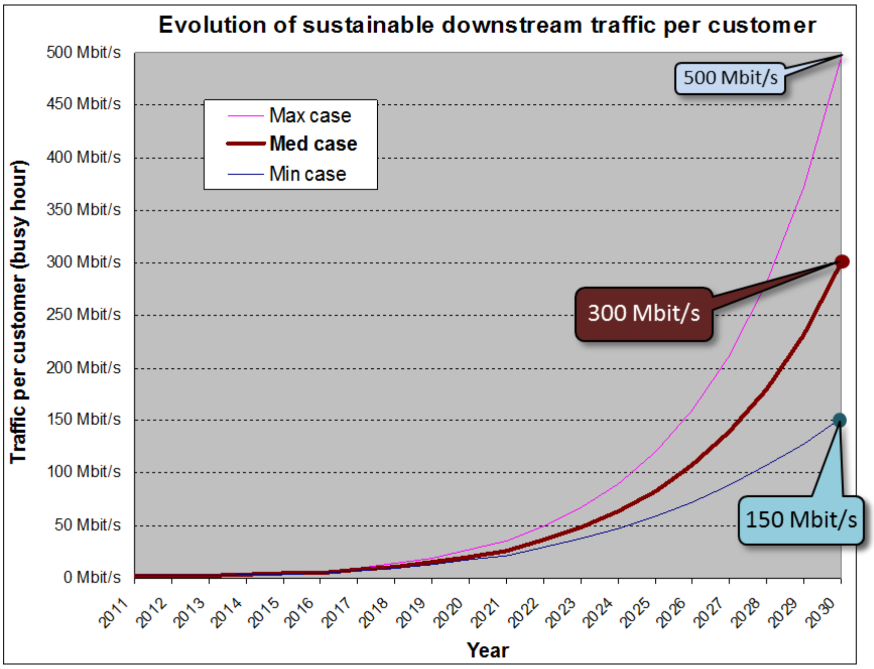


Figure 4 Evolution of sustainable traffic per user

Sustainable busy hour traffic 2020 – 2030*: *(relevant especially for the aggregation and feeder part)*

- Residential: avg. 25 … 300 Mbit/s per ONT
- Business: avg. 100 … 400 Mbit/s per ONT
- Mobile backhaul: avg. 0.5 … 4.5 Gbit/s

Also business traffic and traffic from mobile backhaul are considered in the WP2 traffic model and have been considered for the TCO modelling. However, the overall traffic volume is almost negligible, because of the relatively low access numbers. Nevertheless, these traffics impose high requirements on the functional system design (e.g. QoS, 10G interfaces, E2E protection etc.).

2.3. Aggregation network model

The principle design of the aggregation network is shown in Figure 5. In general, this network segment is split into two parts, the aggregation network I and II. The aggregation network I is always present, connecting the so-called Physical Connection Point 6 (PCP6), which corresponds to the metro access node in the aggressive node consolidation scenario, with the core network location. The aggregation network II is only dimensioned with technology in scenarios without node consolidation (i.e. keeping the 7500 access nodes) or the conservative node consolidation (i.e. keeping 4000 metro access nodes). In the aggressive node consolidation scenario (with 1000 metro access nodes), the aggregation network II is part of the feeder network and dimensioning subject to the specific technology used in the ODN.

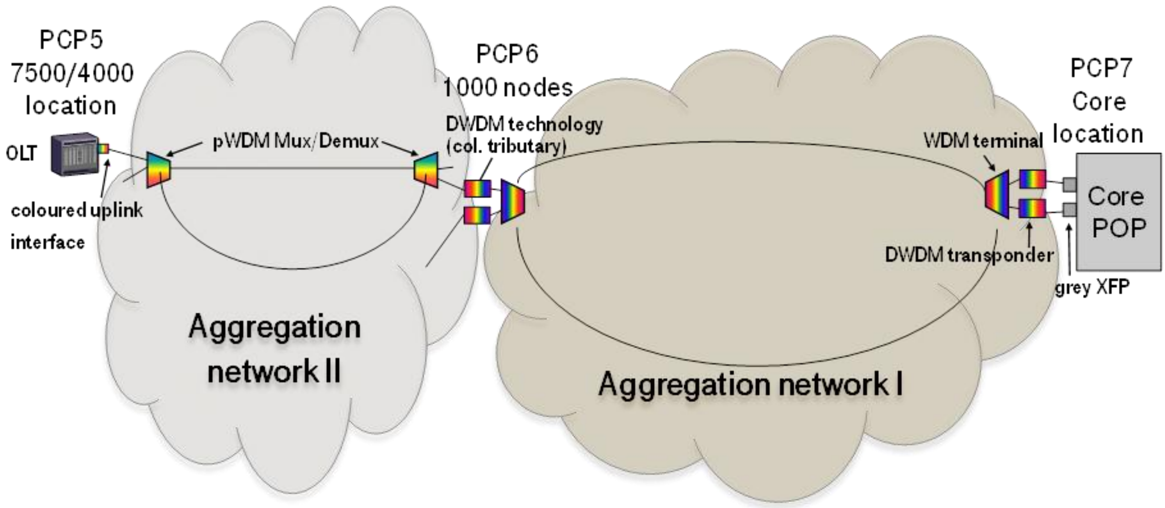


Figure 5 Aggregation cost model

From a detailed transport technology perspective, WDM in different flavours is used. The uplink interface of the OLT is a coloured interface. Depending on the consolidation scenario, the OLT uplink interfaces are multiplexed first with pWDM technology between PCP5 (access node) and PCP6 and between PCP6 and PCP7 (core node) DWDM technology is used or the DWDM technology is used directly. At the core location, DWDM transponders are used to support grey or colourless interfaces at routers. From the Ethernet layer perspective, 10Gbit/s interfaces transparently transmitted over the WDM transport layer between PCP5 and PCP7 are assumed. In addition, a price decrease is assumed, while power costs are also taken into account. Beside active technology, passive components are taken into account as well with a one-time investment fee per required fibre per kilometre.

3. Case Studies

This section introduces the characteristics defining each case study of the cost assessment, which are:

- Network scenario: Area, node consolidation degree, penetration curve and duct availability
- Technology
- Protection (Feeder fibre or end-to-end protection)
- Open Access

3.1. Network scenarios

3.1.1. Areas

In OASE, three types of area have been studied as proposed in Deliverable D5.1 [3]:

- Dense Urban areas: these are the most populated areas that have thousands of households per square kilometre.
- Urban areas: these areas have an average of hundreds of households per square kilometre.
- Rural areas are the less populated areas with tens of households per square kilometre.

Any area or region of Europe can be associated to one of these three areas depending on the household density.

3.1.2. Node consolidation

As introduced in D5.1 [3], traditional access areas (whose central office is referred as access node) can be grouped into larger areas so that the total number of central offices can be reduced, expecting also a reduction of the associated costs. The larger areas tend to be called NGOA service areas, and their central offices are labelled as metro access nodes.
The node consolidation degree is defined as the relative difference between the number of traditional access nodes and the number of metro access nodes in a given network scenario. The main difference in the network architecture is shown in Figure 6. It can be observed that in non-node consolidation scenarios, the OLT is located at the local exchange (PCP5), whereas in node consolidation scenarios, the OLT is located at the central access node (CAN) at PCP6 and requires the feeder fibre (referred as LL5).

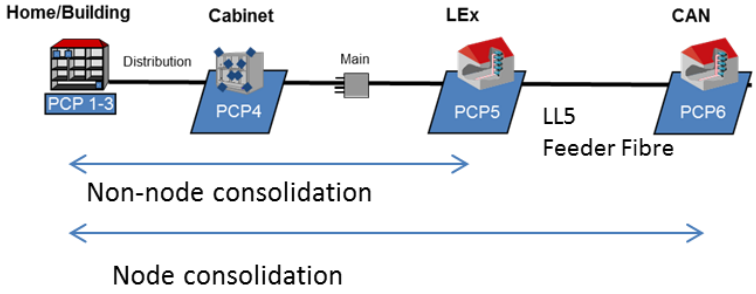


Figure 6 Non-node consolidation reaches up to the local exchange (PCP5), whereas node consolidation reaches the central access node (PCP6)

In this work the aggressive node consolidation have been compared with the non-node consolidation case, which considers a node consolidation degree of 87.5%, that is, a reduction to only a seventh of the traditional access areas.
Our reference scenario considers 7500 traditional access areas and hence, the aggressive node consolidation has 1000 metro access nodes, whereas the conservative node consolidation has

4000 metro access nodes. However, any area of Europe can be mapped to one of these scenarios, which were described in D5.1 [3].

3.1.3. PIP and NP penetration curves

In the cost assessment, it is important to define at which rate the network is being installed and users are expected to join it. Hence, two penetration curves have been considered [4]:

- Physical infrastructure provider (PIP) penetration curve indicates the infrastructure installation rate. In the TONIC tool two curves have been defined:
  - "Everything in 2010" considers the entire fibre infrastructure to be rolled out in 2010, taking into account the selected duct availability (see Section 3.1.4).
  - "Greenfield in 2020" considers Greenfield scenario in 2020 so that NGOA is directly installed and deployed. This option has been selected to perform the Greenfield studies presented in Section 4.4.
- Network provider (NP) penetration curve indicates the rate at which users want to have access to the network. It is defined as the percentage of users in the area that are connected to the network. In the TONIC tool different curves have been defined as shown in Figure 7 in Deliverable D6.2 [7]:
  - "Likely" which reaches more than 70% of the users in 2030.
  - "Conservative" which is less than 65% in 2030.
  - "Aggressive" which reaches 80% already at 2020.

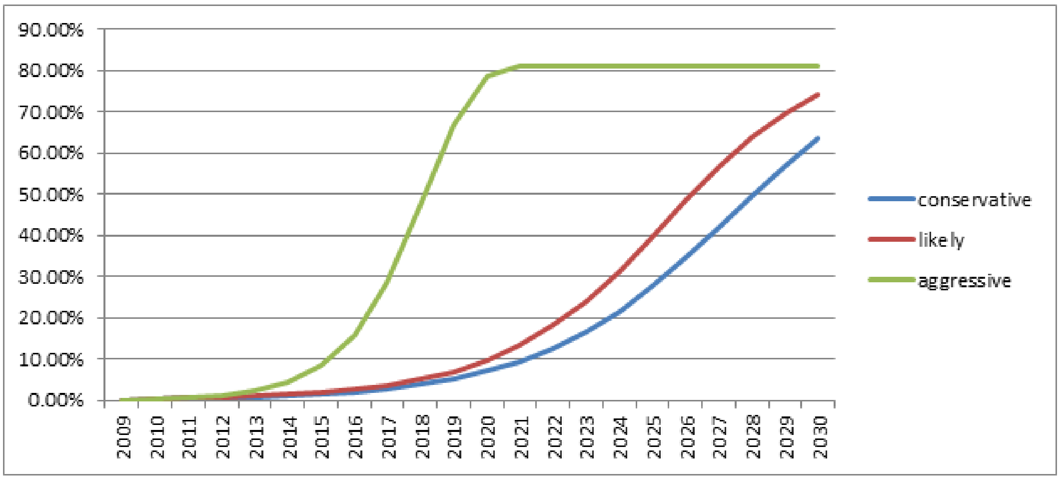


Figure 7 Network Provider (NP) penetration curves

3.1.4. Duct availability in First mile infrastructure segment

Duct availability is a key parameter for the cost of deploying fibre in a selected area. Unfortunately, there is only limited information available on ducts, typically either in a very fine granular level (per sub-street segment) or in too broad level (country level). For analysing the strategic impact, a level of detail in-between is most useful. Therefore information from carriers in the project has been requested, analysed and four different models (S, M, L, XL) beside the model of pure Greenfield (GF) defined. This model includes the availability of ducts in terms of number of free / available ducts per distribution and main cable section per geographic area.

Overall 15 different parameter combinations for the areas exist, but the analysis is limited to the brownfield scenarios “S” (small duct space availability) and “XL” (extra-large duct space availability) reflecting some kind of extreme case analysis and pure Greenfield as the potential upper end of costs. Some basic information on the scenarios:

- “Greenfield”: as the name indicates, it corresponds to the Greenfield scenario where no duct is available and hence, all infrastructures should be installed.
- “S” refers to the brownfield scenario (it corresponds to the “-“ option of Figure 23 in D5.2 [1]). In this scenario, only a limited percentage of ducts (between 1 and 3 empty ducts) is available (main cable section between 50% in dense urban, 28% in urban and 10% in rural; distribution cable section between 12% for dense urban, 8% in urban and 1% in rural).
- “XL” refers to the brownfield scenario (it corresponds to the “++“ option of Figure 23 in D5.2). In this scenario, a high percentage of ducts (between 1 and 3 empty ducts) is available (main cable section between 94% in dense urban, 73% in urban and 55% in rural; distribution cable section between 70% for dense urban, 30% in urban and 15% in rural).

More details on the different models are presented in Section 4.1 of D5.2 [1].

3.2. Technologies

Figure 8 gives an overview of the selected reference and NGOA architectures as input for TCO assessment provided by WP3 and WP4 [5,6]. This section gives a short description of the architectures as well as the location of the equipment and the considered splitting ratios.

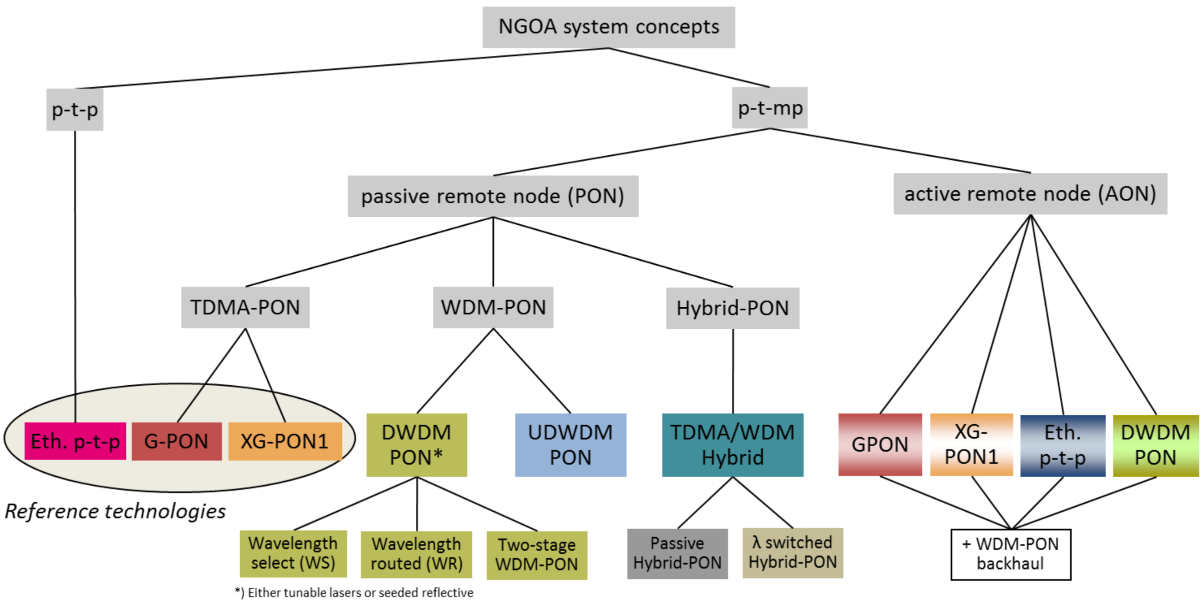


Figure 8 OASE considered NGOA technologies

3.2.1. GPON and XGPON

The GPON architecture considered in OASE, as shown in Figure 9, utilises a single power splitter at PCP4. In order to cope with the required bandwidth and transmission distances, a 1:32 power splitter has been considered in the scenarios without node consolidation, whereas four 1:8 power splitters have been considered in the aggressive node consolidation scenarios. Reach Extenders are required at the LEx (PCP5) in all conservative and aggressive node consolidated areas. From PCP6 the network aggregation presented in Section 2.3 is considered.

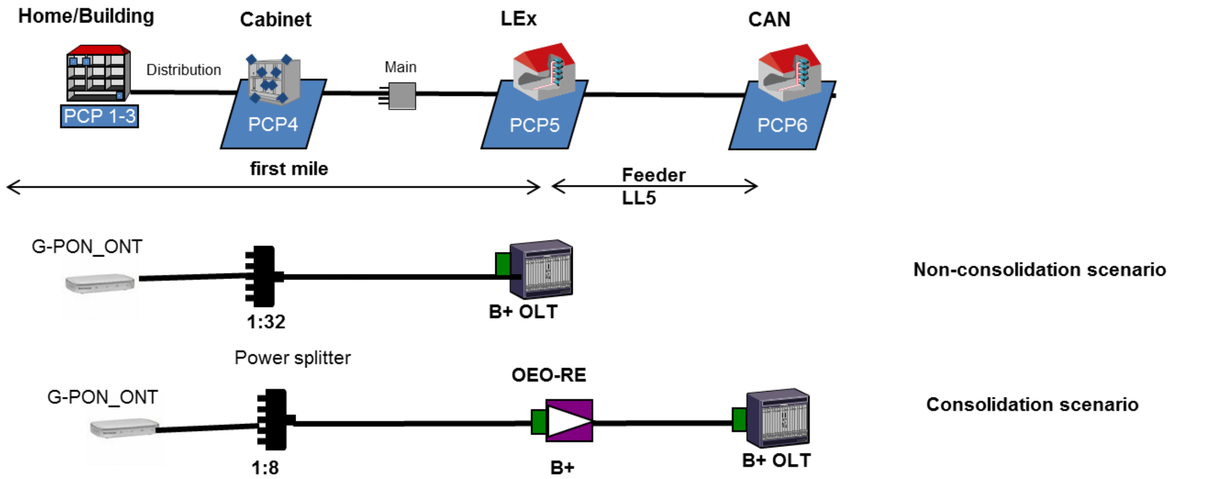


Figure 9 GPON architecture

The XGPON architecture is similar to the GPON architecture but utilises XG-PON equipment at ONT and OLT. Since the bitrate of XGPON is higher than GPON, the power splitters installed in the field can have higher splitting ratios. Therefore, in the consolidation scenario, XGPON uses two 1:16 splitters, reducing the number of splitters and fibres with respect to GPON.

3.2.2. AON homerun and active star

An AON homerun architecture (also called point-to-point Ethernet and referred in this document as AON P2P) is shown in Figure 10. Each subscriber has a dedicated fibre connection from the home ONT to the OLT at the LEx.

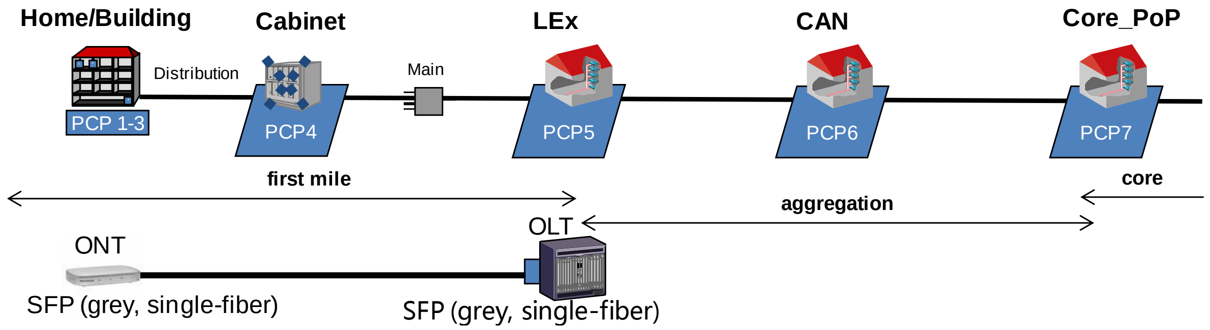


Figure 10 AON P2P, reference scenario, non-node consolidation

Unlike the homerun architecture, an active star architecture employs active remote node (ARN) topology, as illustrated in Figure 11. The active equipment (in this case Ethernet switches) are located in either cabinet or building locations where upstream data from a group of end-users is aggregated, then the uplink of these Ethernet switches are further aggregated into either a single or a few feeder fibres towards the second Ethernet switch at LEx (PCP5) or CAN (PCP6).

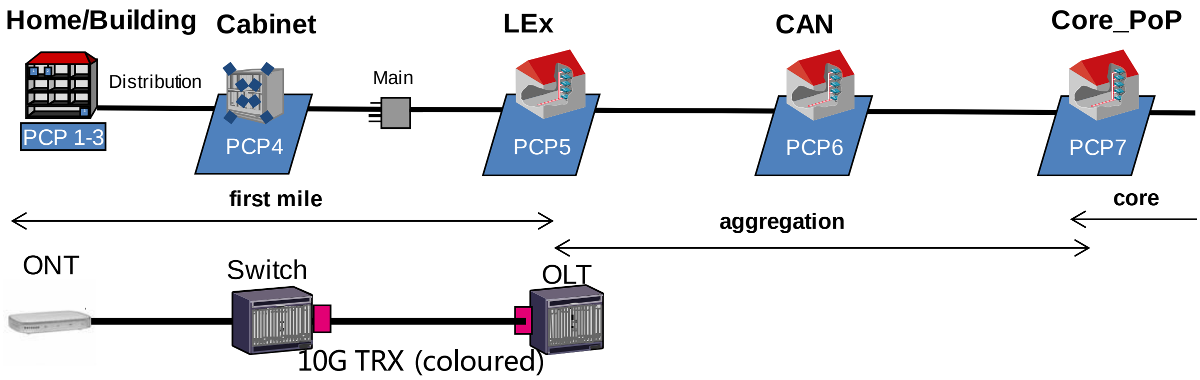


Figure 11 AON active star, reference scenario, non-node consolidation

Both AON homerun and active star architecture are capable of offering all subscribers with the OASE target sustainable bandwidth (300 or 500 Mbps per customer) over the 20 years study period without technology migration, therefore in D5.3 studies they are implemented as the reference architecture for the non-node consolidation scenario (7500 nodes scenario) compared to other NGOA architectures. Both the AON homerun and active star architecture are modelled from the user's home (PCP1) till the LEx (PCP5) in a non-node consolidation scenario. After the LEx, the network is considered as part of aggregation network.
In addition to this, an active star variant allowing for smaller deployments is shown below in Figure 12. By utilising the aggregation network heavily, it may be possible to target areas where demand is higher, as well as remove all equipment from PCP5. This should allow for smaller, more organic network deployments by leveraging the aggregation network more heavily.

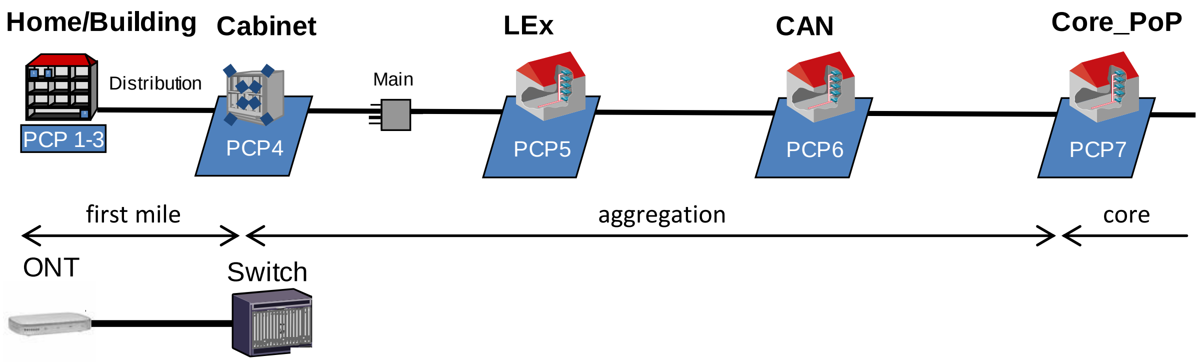


Figure 12 AON active star with extensive use of the aggregation network.

3.2.3. Wavelength-routed WDM PON (WR WDM PON)

Wavelength-routed WDM PON architecture, as described in Figure 13, assigns one wavelength to each user of the network. The architecture consists of the conventional components of a Passive Optical Network (PON): (i) an OLT located at a CAN, (ii) ONTs at each user's home; (iii) Arrayed Waveguide Gratings (AWGs) at Remote Nodes (RNs) between user and CAN to form the point-to-multipoint network topology; the use of C/L and S/L band splitters and a spacing down to 25-GHz allow client counts of 80, 160 and 320 in one feeder fiber. The RN can be either at the street cabinet or legacy local exchange office. The detailed description of this architecture can be found in D4.2 [6]

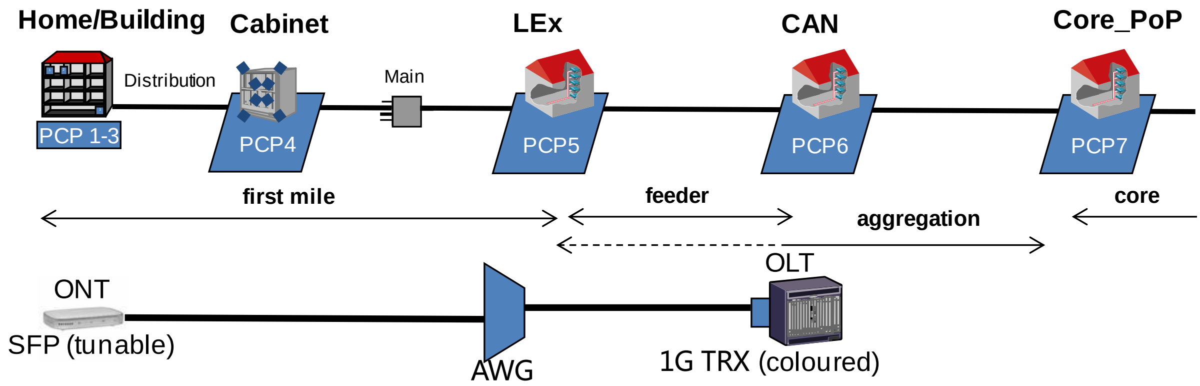


Figure 13 Wavelength Routed WDM-PON architecture

In the studies within this deliverable, the WR-WDM-PON is implemented with two variations. The first implementation has an 80 channel AWG located at LEx (PCP5). ONTs with tunable lasers and APD receivers are used at the user's home (PCP1). From PCP5 until PCP1 there are point-to point-fibre connections; the AWG aggregates every 80 fibers into one feeder fiber and uplinks to the OLT at the CAN (PCP6). When WR-WDM-PON is modelled for node consolidation scenario studies, the aggregation network model starts from CAN (PCP6) to Core (PCP7). In common with the AON homerun architecture, this WR-WDM-PON implementation has a point-to-point fibre infrastructure from PCP1 to PCP5, therefore this architecture can be an option for AON homerun migration from a non-node consolidation scenario to a node-consolidated architecture without changing the fiber infrastructure in the optical distribution network (ODN).
The second implementation has the 80 channel AWG located at cabinet (PCP4), and then feeder fibres links PCP4 and PCP6. This scenario can be used for study of migration from GPON reference architecture where 1:32 power splitters are originally installed at PCP4.

3.2.4. Wavelength-Selective WDM PON (WS WDM PON)

Wavelength-Selective WDM-PON is similar to the WR WDM PON described above through its utilisation of a WDM channel between the OLT and the ONT.

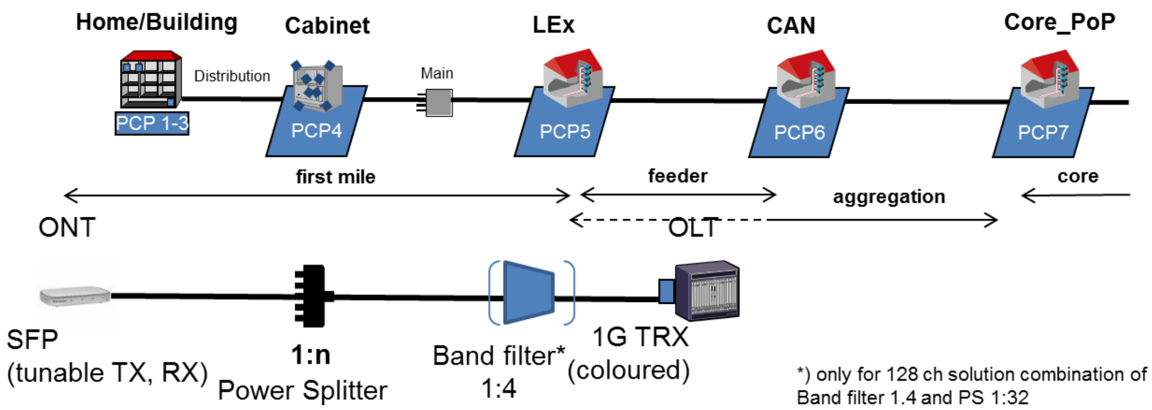


Figure 14 Tunable-based WS-WDM-PON: assignment to PCP sites (D4.2.2 [6])

However, where the WR-WDM PON provides this channel by use of an AWG to distribute individual wavelengths to the customers, the WS-WDM PON utilises a power splitter and relies on the clients filtering the incoming channel in order to transmit and receive on the correct wavelength. The utilisation of a power splitter has a number of implications on the system design, notably reduced reach, decreased isolation between customers, and high cost

through necessitating the usage of expensive tuneable filters. However, these issues are offset by its inherent potential for simple migration from GPON by utilising the already-deployed optical splitters in the passive infrastructure. One of the interesting assessments will be the trade-off between higher system cost and cost savings through passive infrastructure re-use.
WS-WDM PON exists in three variants, based around the number of wavelengths per fibre. The 32 channel system provides the best alignment with GPON optical splitter deployments, while the 64 channel system offers the possibility of higher fan out with associated reach penalty. Finally, a 128 wavelength system is available, utilising a DWDM band splitter located in PCP5 to create 4 32 way splits. This offers the highest fan-out while still retaining compatibility with the conventional GPON passive infrastructure, but requires the use of EDFA boosters/pre-amplifiers co-located with the line cards with corresponding increase in system cost.
Further information about this architecture variant may be found in D4.2 [6].

3.2.5. UDWDM

At a high level, the Ultra-dense WDM PON (UDWDM PON) solution bears similarity to the WS-WDM PON system with band-pass filter. UD systems utilise wavelengths which are densely packed together. This allows "standard" 100G spacing AWGs to act as band-filters at no additional cost.

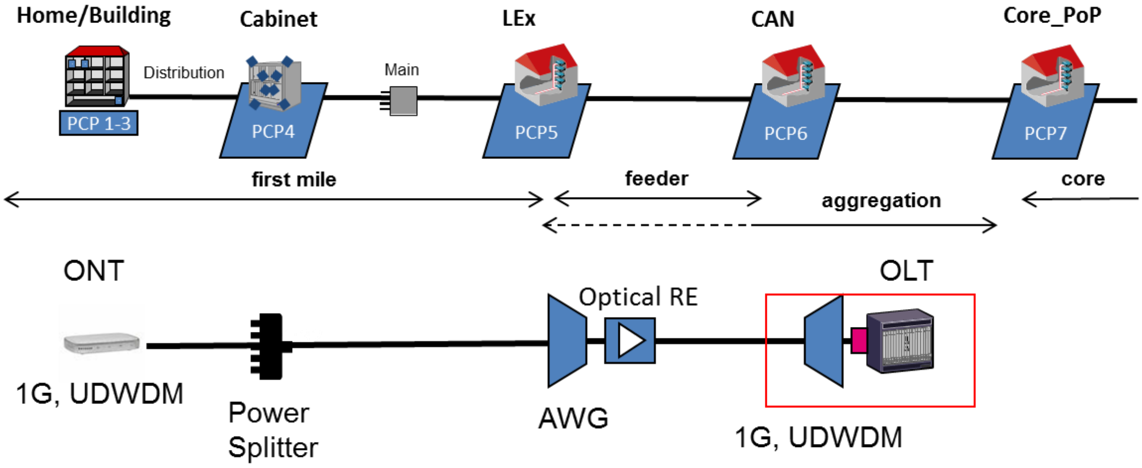


Figure 15 The UDWDM System Concept

The UDWDM OLT produces 320 wavelengths on one fibre, compared to the 128 wavelengths made possible by the highest-density WS-WDM PON variant. Commonly, a 1:40 AWG is used to create 40 fibre channels of 8 wavelengths each, which are distributed to 1:8 optical splitters. Other splitting ratios are possible (for example by utilising a 1:32 optical split and a 1:20 AWG), however while they are tempting for a scenario seeking to migrate from GPON and re-use passive infrastructure, high fan-out has an adverse effect on system reach.
Due to the nature of the system, the ONTs for UDWDM PON are cheaper than those utilised by WS-WDM PON, however the OLTs are more expensive per wavelength. It will therefore be interesting to see how these two factors balance out in a real-world assessment.
More information about this architecture can be found in Section 5.2.3 of D4.2 [6].

3.2.6. Passive Hybrid PON

The passive Hybrid PON (HPON) considered in these studies is shown in Figure 16. It consists of two splitting points: the power splitter located at PCP4 and the wavelength splitter (Array Waveguide: AWG) at PCP5. The OLT is located at PCP5 for the non-node consolidation studies and at PCP6 for the consolidation studies. Two different splitting ratios have been considered:

- "HPON40": considers an AWG with 40 channels, and a 1:32 power splitter. APD receivers are considered at the ONT.
- "HPON80" considers an AWG with 80 channels and a 1:16 power splitter. PIN receivers are assumed to be used at the ONTs and hence, reach extenders may be needed at PCP5.

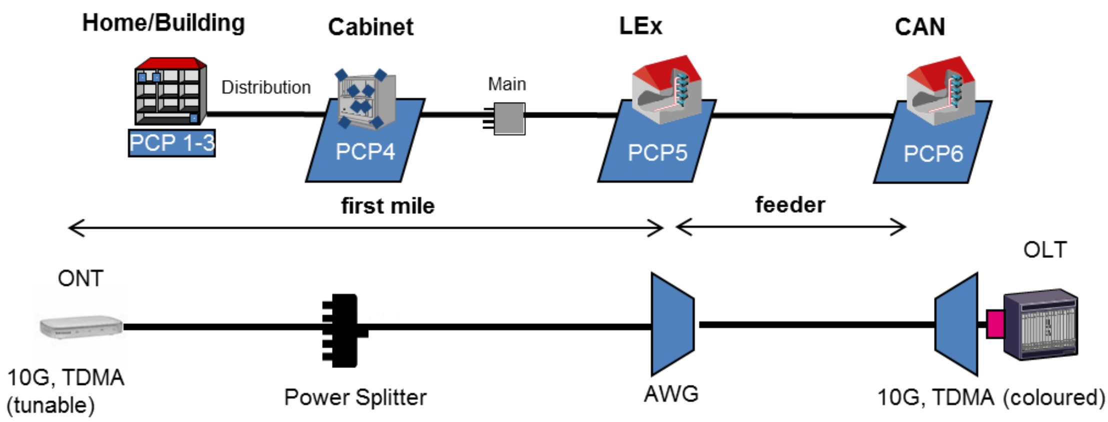


Figure 16 HPON architecture in case of node consolidation

Both architectures have the same client count but HPON80 offers higher bandwidth than HPON40.

3.2.7. WDM PON backhauling AON

A WDM PON backhauling solution can be adopted in order to migrate AON active star architectures from a non-node consolidation scenario to a node consolidation scenario by replacing the active equipment previously located at PCP5 with passive AWGs, meanwhile a WDM OLT is placed at the CAN (PCP6), thus the access network is extended, and the aggregation network starts from PCP6 to PCP7.

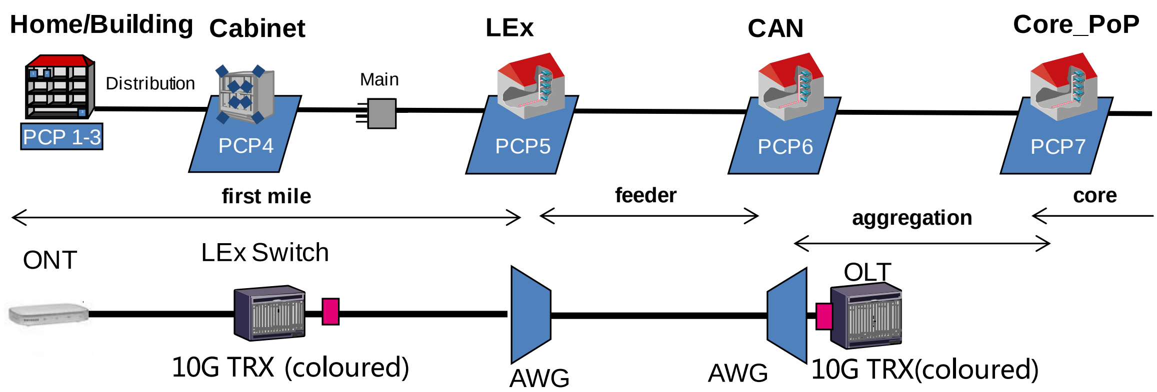


Figure 17 WDM PON backhauling AON

The migration from the reference AON active star outlined in the sections above to WDM PON backhauling architecture can be done smoothly without changing the fibre infrastructure in the ODN from PCP1 to PCP5, the ONTs at PCP1 and switches at PCP4 can be reused as well.

3.2.8. Two-stage WDM PON

The D5.3 implementation of two-stage WDM PON is indicated in Figure 18. The first stage WDM PON system connecting each subscriber with 1Gbps link from home (PCP1) to LEx (PCP5), where passive AWG filters with 80 channel capacity are located at a street cabinet (PCP4). The second stage WDM system is modelled from PCP5 till PCP6. The WDM OLT-2 located at CAN (PCP6) provides the backhauling solution to the WDM OLT-1 at LEx with 10Gbps links.

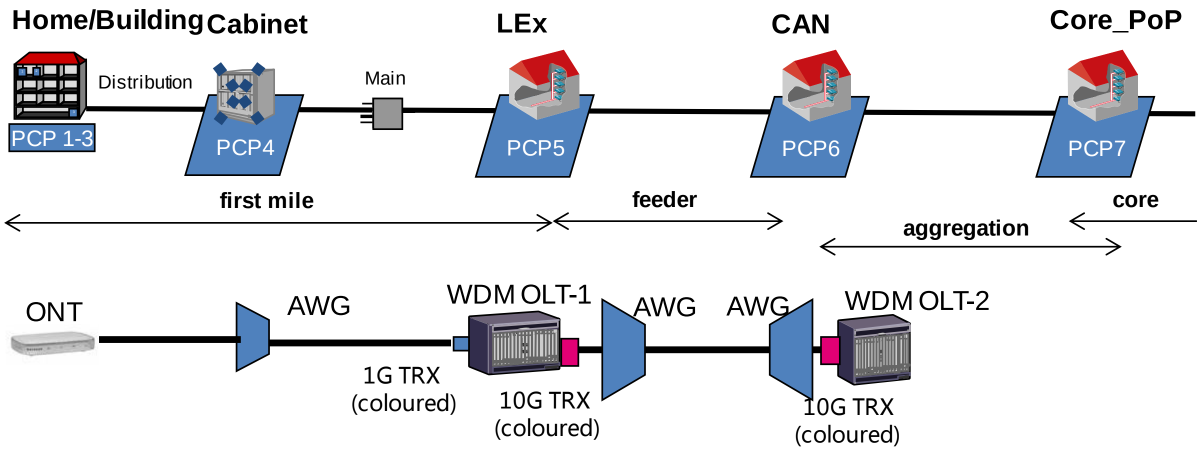


Figure 18 Two-stage WDM PON

3.3. Protection scenarios

Here we discuss the protection scenarios that will be included in the cost assessment: in particular, we analyse two protection possibilities per architecture: FF protection vs. FF+OLT protection, and compare them with the unprotected case. We have also limited the studies to consider the DU and R areas with 1000 and 7500 nodes (extreme cases).

3.3.1. Feeder Fibre Protection

The first step towards a protected access network is to offer a protected feeder fibre as proposed by the ITU for PONs. The increase of connection availability granted by this technique has been analysed in D3.2 [5]. The implementation of this protection has been proposed by WP3 and the associated cost has been analysed in WP5 and presented in Section 4.4. Since the feeder fibre is deployed from PCP5 and PCP6, this protection scheme will be applied to the conservative and aggressive node consolidation scenarios. The architectures that have been evaluated are: GPON (Section 3.2.1), XGPON (Section 3.2.1), WR WDM PON (Section 3.2.3), WS WDM PON (Section 3.2.4), HPON (Section 3.2.6), and AON star WDM Backhaul (Section 3.2.7).
Let us present an example showing feeder fibre protection for the passive HPON, which is depicted in Figure 19. It can be observed that the OLT is duplicated, and each OLT is linked to one feeder fibre (either working or protection fibre). The M:1 AWG splitter at PCP5 should be replaced by a M:2 AWG. In case a reach extender was required at PCP5, it should be

duplicated. All these equipment costs as well as the disjoint feeder fibre costs have been evaluated and presented in Section 4.4.

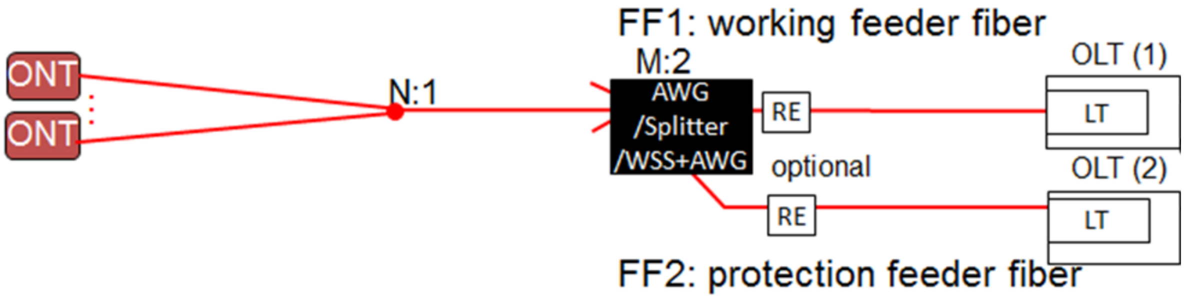


Figure 19 Feeder Fiber (FF) protection for HPON architecture

3.3.2. Distribution Fibre Protection

In addition to the feeder section of the network a duplicate path to the customer could also be provided in the distribution section. The combination of these approaches together with the right link in the customer premises equipment would provide a fully resilient network capable of restoring any single problem on the path up to the customer. Of course, this would increase the cost and could therefore prove an expensive overkill for those seldom cases in which the network breaks. The FIT-rates or MTBF values of network equipment will already lead to a very high reliability for the end customer. Considering the number of customers connected to one feeder fibre, a resiliency scheme in this particular network section could make sense. In the case of the distribution section, you would need convincing arguments and selling points to motivate customers to pay more for this additional investment. This is unlikely in the distribution segment, as discussions have revealed that many customers and even SMEs are not really willing to pay an extra (not even small) cost to get a higher reliability guarantee on their network connection.

Resilient network architectures for the distribution network can be constructed in different ways and all architectures will try to reuse as much as possible of the existing infrastructure and trenching. In extension to the models described in D5.2 Section 4.2.2, we made analytical calculation models incorporating a resilient path to each end customer. Estimating the extra infrastructure and installation cost for providing a redundant path to the customer is fairly straightforward for the analytical examples constructed before. Figure 20 gives an example of the topology of a double street (2x2 times) in which fat (red, green) lines show the additional trenching required for adding redundancy. For analytically solving the extra cost of these redundant paths, we cut out a square in the middle spanning the same area as the original block topology and which will result in an equal additional trenching length and cable length as the original block albeit taking mirroring in mind.

Clearly we need to count the number of connection points to the left and right of the network for any street based analytical model. This means that we will need an extra $n \cdot l$ (in case of a simplified or double street topology) or $(\frac{n}{2}) \cdot l$ (in case of a street topology).

For calculating the cabling length we refer to Figure 21 which gives a diagram of the two first quadrants of the square shown in the previous figure. For adding a redundant cable for a house in quadrant A, we can envisage this as installing a cable up to point a' and from there install a cable up to the redundant connection point b which takes an extra length of $n \cdot l$ per customer. This same reasoning holds for all customers in the four quadrants. As such the extra cable length to install the redundancy in the network is the same as the original cable length for the topology with in addition a length of $n^3 \cdot l$.

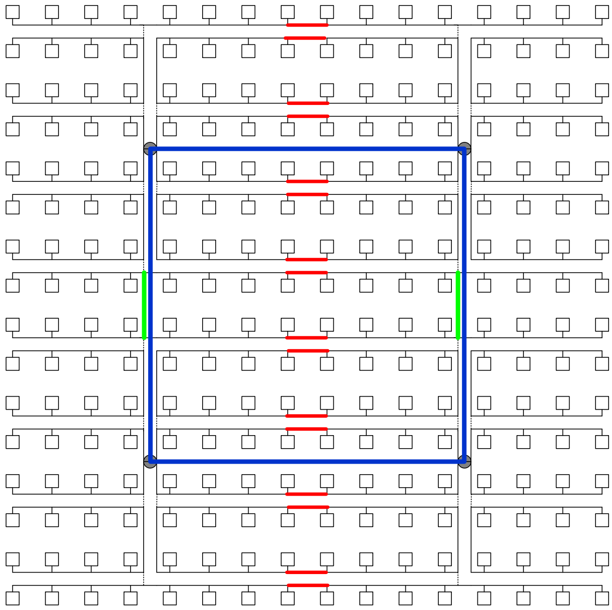


Figure 20 Additional trenching required on top of the original structure in order to get a fully resilient network.

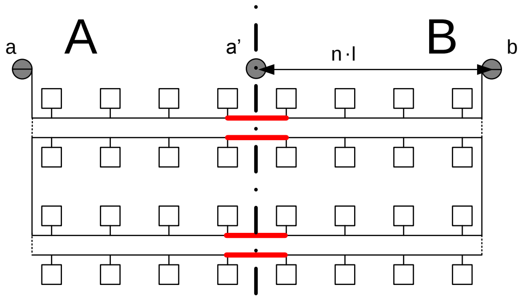


Figure 21 Detailed view of the upper half of the resiliency structure for evaluating the analytical calculation structure and formula.

These structures allow us to calculate the cost of providing a resilient network for the distribution section. Still, the structure is not the same as the geometric model used in the TONIC tool. As mentioned before, there were concerns about whether resilience in the distribution section of the network would ever increase the consumers' willingness to pay. As such, the resiliency models shown above were not incorporated into the TONIC tool [1]. This means that the calculations cannot be easily translated to the other results in this deliverable. The following results will therefore focus on relative extra cost for the distribution section making the relation easier with the outcome of all other studies.

In Figure 22, the relative extra cost (percentage) an operator has to invest to construct a fully resilient distribution network in two extreme cases is shown. On the left hand side the extra cost of providing a fully resilient network in a dense urban area is shown in which the fibre cost of high density fibre-cables is taken. The costs of trenching and fibre used in this case are respectively 50 and 0.012 euro per meter. This results, in all analytical models, to an extra cost as low as 3% at an aggregation level of 1000 per flexibility point. The extra investment costs could go below 10% when the aggregation level per flexibility point is higher than 100 customers. On the right hand side the situation is shown for a rural case in which the highest TONIC cost for fibre has been used, with a trenching and fibre cost of 20 and 0.075 euro per meter respectively. Clearly in this case the sweet spot is to be found at 100-200 customers per flexibility point and even in this case the resilience cost only reduces to around 10%. In all other cases the cost will most probably be 20% (or higher) more costly than not taking resilience into account.

It should be noted that these figures can only be interpreted as illustrative, as (1) they are not constructed with the same background and geometric model as has been used in TONIC [1] and (2) many aspects have not been investigated in detail (e.g. cable cut repair, asset management, installation, etc.) which would all add to the costs of resiliency.

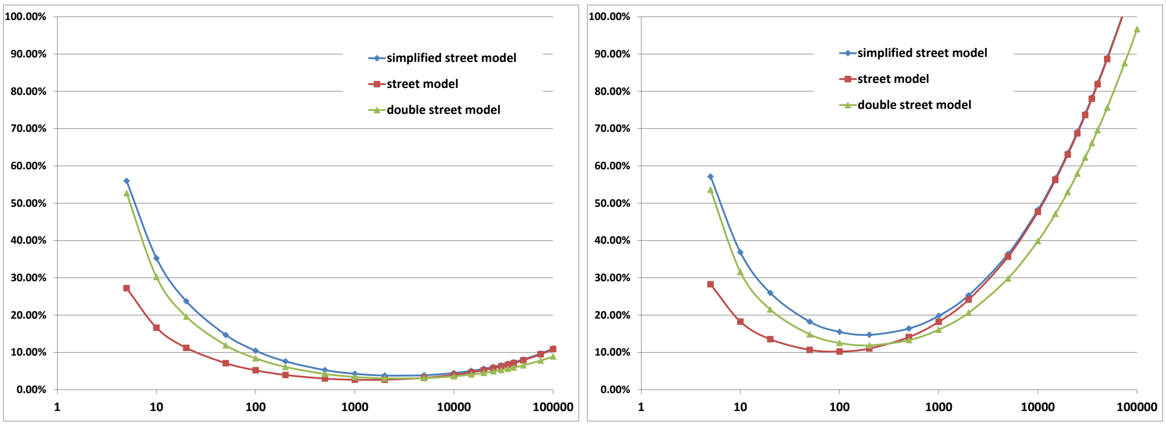


Figure 22 Additional cost estimated for installation of a fully resilient distribution network as a factor of the size (in customers) of each separated distribution section.

3.4. Open Access

The costs of open access have been investigated in a close cooperation effort, which was setup between WP3 (D3.3) and WP6 (D6.3). They identified three levels at which the network could be opened –bitstream, wavelength and fibre. This can be done in an unbundling scenario (opening up the network of a previously vertically integrated player) or an open access scenario (competitive access on top of open network).

In the case of bitstream no additional equipment must be placed inside the optical network. In the other two cases, extra equipment has to be added to the network and more details on this open access related equipment for the whole set of NGOA architectures can be found in D3.3 Section 5. The related cost for the aggregation networks is described in D3.3 Section 6.

Based on the identified business requirements, WP6 focused on the following list of architectures: AON for fibre open access, HPON and WR WDM-PON (AWG and multi feeder fibre based) for wavelength open access.

The open access cost was split in three parts within WP6 (D6.3 Section 2.4): equipment related costs, management and patching related costs and business related costs. These costs are then used to calculate the impact of open access or unbundling on the business cases for the PIP and the NP. A lot of the input information for this open access cost originates from WP5.

- The equipment related cost for fibre open access was defined jointly by WP3 and WP6. The equipment related costs for wavelength open access was calculated by WP5 based on the equipment models from WP3.
- In the case of fibre open access an additional patching level has to be installed and WP5 provided WP6 with costs for this patching panel and the actual patching of customers (physical patching, operational process) on a per migrating customer basis. In the case of wavelength open access, the patching is handled in an automated or semi-automated manner and WP5 gave an indication of the remaining administrative tasks with WP6 (logical patching).
- The business related costs were described by WP6.

As mentioned for all details on the architectures we refer to D3.3 and for further analysis of the impact on the costs of introducing open access, we refer to D6.3.

4. NGOA Cost Assessment: Migration: NP Brownfield

This section presents the first NGOA assessment considering the migration from existing traditional optical access solutions to Next Generation Access networks, which is referred in this document as "**Migration: NP Brownfield**" studies. In this case, infrastructure and equipment exists for the non-node consolidation scenario when having GPON, AON or other traditional optical access networks. This study evaluates the increase of costs to migrate to NGOA solutions when keeping non-node consolidation or when considering aggressive node consolidation.

The migration **NP Greenfield** which assumes a migration from non-optical access networks (e.g. copper network) where some ducts may be available to be used by optical cables, is presented in Section 4.2. Furthermore, the cost evaluation from a **pure Greenfield** scenario, that is, no NP or PIP available is presented in Section 4.3.

The NGOA cost assessment analyses the cost of the following architectures and scenarios listed in Table 1.

Table 1 Evaluated NGOA architectures

Architecture	Pure/NP Greenfield	Migration: NP Brownfield	
	Aggressive consolidation	Non-node consolidation	Aggressive consolidation
GPON 1:8	√	√	√
XGPON 1:16	√	√	√
XGPON 1:32			√
HPON 1:40	√	√	√
HPON 1:80	√	√	√
WS WDM PON 1:64	√	√	√
WS WDM PON 1:128	√	√	√
WR WDM PON 1:80	√		√
UDWDM	√	√	√
AON star WDM backhaul	√		√
AON p2p		√	

4.1. Introduction: Migration: NP Brownfield

This chapter addresses the implementation and operational aspects of the network migration towards NGOA architectures. The technical migration aspects are described in WP3 for the different architecture concepts. The migration process comprises all activities which are needed to switchover customers from existing fibre based reference architecture to a new NGOA architecture. The whole migration process will be distinguished between migration planning and preparation activities, the basic rollout of the NGOA architecture and customer individual migration activities. The first two parts include the migration planning, general IT/NMS adaptations, the installation & commissioning of the new NGOA system components and, if necessary, also passive infrastructure upgrades. The second part comprises the customer individual migration including customer specific network and service (re-)configurations and, without ODN coexistence, also manual switchover on physical layer. The proposed high level model of the migration process is described in D5.2. The general migration process steps are given in Figure 23.

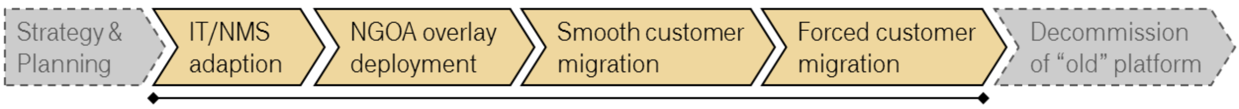


Figure 23 Considered general migration steps

NGOA architectures which are coexistent with an existing PON based ODN allow executing most of the network related migration activities in the CO without the need for ODN infrastructure upgrade and thus minimal labour work in the field. Architectures which support a power splitter infrastructure are: HPON; WS-WDM PON; UDWDM-PON. General migration activities in case of ODN coexistence are:

- Installation and commissioning of the NGOA systems
- Introduction of a migration specific WDM coupler per power splitting PON during the maintenance window (usually overnight). Requires adaptation of the NMS configuration and test routines (Customer impact possible)
- Customer flow point and service profile (re-)configuration, if requested
- Demand-driven activation through ONT delivery and plug-in by user (auto-configuration)

NGOA architectures which are not coexistent with an existing PON based ODN, require a parallel ODN overlay infrastructure up to the "last" power splitter (e.g. up to the cabinet). This results in additional effort in the field or even in the customer buildings. Architectures which do not support a power splitter infrastructure are: DWDM-PON; AON P2P; AON active star. These architectures require additional activities as following:

- Through-connection of parallel ODN infrastructure using upgrade fibres, if available, otherwise deployment of new fibre cables
- Fibre termination at fibre patch panel in the field (e.g. at cabinet) or in larger buildings in case of second stage power splitter
- Demand driven manual switchover of physical user lines at patch panel

4.1.1. Migration scenario – Base assumptions

The TCO analysis focuses on the migration starting from traditional access networks such as GPON or AON P2P towards NGOA PON architectures. GPON is used as traditional access area for all the architectures except for WR-WDM PON and NG-AON, whose migration starts from a AON P2P. Three Geo-types (DU, U, R) as well as different node consolidation scenario (non-node consolidation and aggressive node consolidation) have been investigated. A base demand evolution with 300 Mbps sustainable traffic per user and a penetration evolution from 10% in 2020 to 74% in 2030 (so-called "likely" penetration curve) is considered. The migration starts in 2020 and is assumed to take just one year to complete, which is realistic for one area. In order to see the impact to migrate all the access networks in a country, we also analyse the cost when starting the migration later in Section 7.4.
From 2010 to 2019, the traditional access network is running alone. From 2020 to 2030, two alternative situations are distinguished:

- **„Upgrade/continuation":** the traditional access solution runs till 2030 (case for GPON, XGPON, and AON P2P)
- **„Migration":** NGOA deployment starts in 2020.

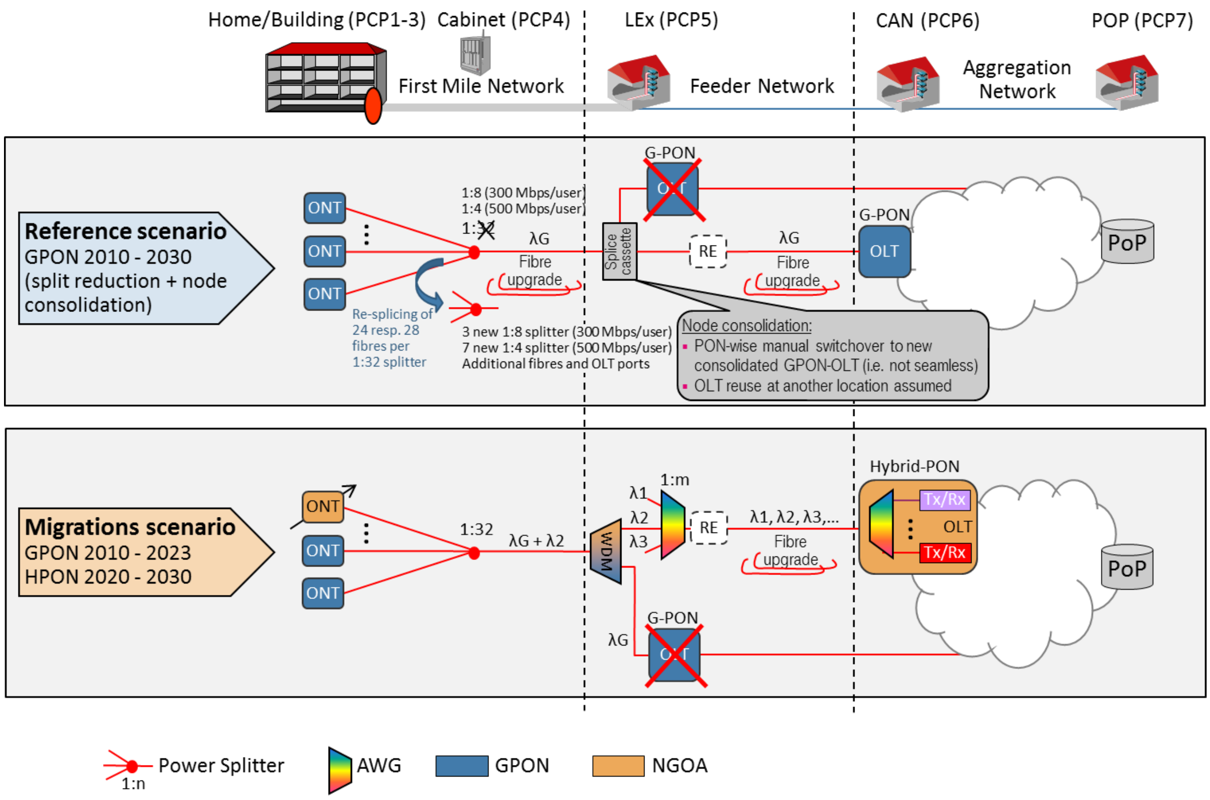


Figure 24 Example HPON migration versus GPON reference in node consolidation

Figure 24 shows the GPON reference and an example migration towards Hybrid PON in a node consolidation scenario. In the reference scenario, a reduction of split ratio is required depending on traffic and penetration evolution, as well as a PON-wise manual switchover from the "old" to the new consolidated GPON-OLT. In the migration scenario, no reduction of splitting ratio is required, because the customers will successively be migrated from the GPON to NGOA during the parallel migration time.
Note: In locations which remain in a non-node consolidation scenario, only a split reduction without switchover of GPONs is required in the reference.
The required migration specific network and infrastructure components for the overlay deployment of traditional and NGOA architectures, based on the schemes proposed in [D3.2] are given in Table 2.

2.1.1. NGOA customer migration

The NGOA overlay migration follows the overlay deployment and is mainly related to the operational part. It deals with a demand-driven customer-wise migration towards NGOA by exploitation of regular occurring provisioning events such as provider changes or service upgrades for minimised customer impact. Figure 25 shows an example evolution of the customer bases on the existing FTTH platform and NGOA depending on migration volumes.
The "Forced" migration phase deals with the complete switchover of all remaining customers to NGOA and decommission of the "old" FTTH platform to avoid long parallel operations over several years.

Table 2 Migration specific efforts per architecture

Migration target architecture	Migration specific components	
	Network element	Infrastructure
	starting from GPON	
WS-WDM PON	• WDM filter per PS-PON for interworking	• Seamless customer migration supported (i.e. no manual switchover of customers) • ODN coexistence • Using existing filter rack in CO
UDWDM PON		
Passive HPON		
Wavelength switched HPON		

WR-WDM PON	-	• No seamless customer migration
		• Parallel fibres up to the “last” power splitter
		  o Upgrade LL4, LL5 fibres (1-stage)
		  o Upgrade LL3, LL4, LL5 fibres (2-stage)
		• Fibre patch panel behind the “last” power splitter
		  o at PCP4 (1-stage)
		  o at PCP3 (2-stage)
		• Re-splicing of power splitter, if not connector based in the basic rollout

Two-stage WDM PON		
	starting from AON P2P	
WR-WDM PON (AWG in CO)	-	• No seamless customer migration • ODN coexistence • Extension of ODF cross-connect at PCP5 (Upgrade LL5 fibres)
Passive HPON (AWG and PS in CO)		

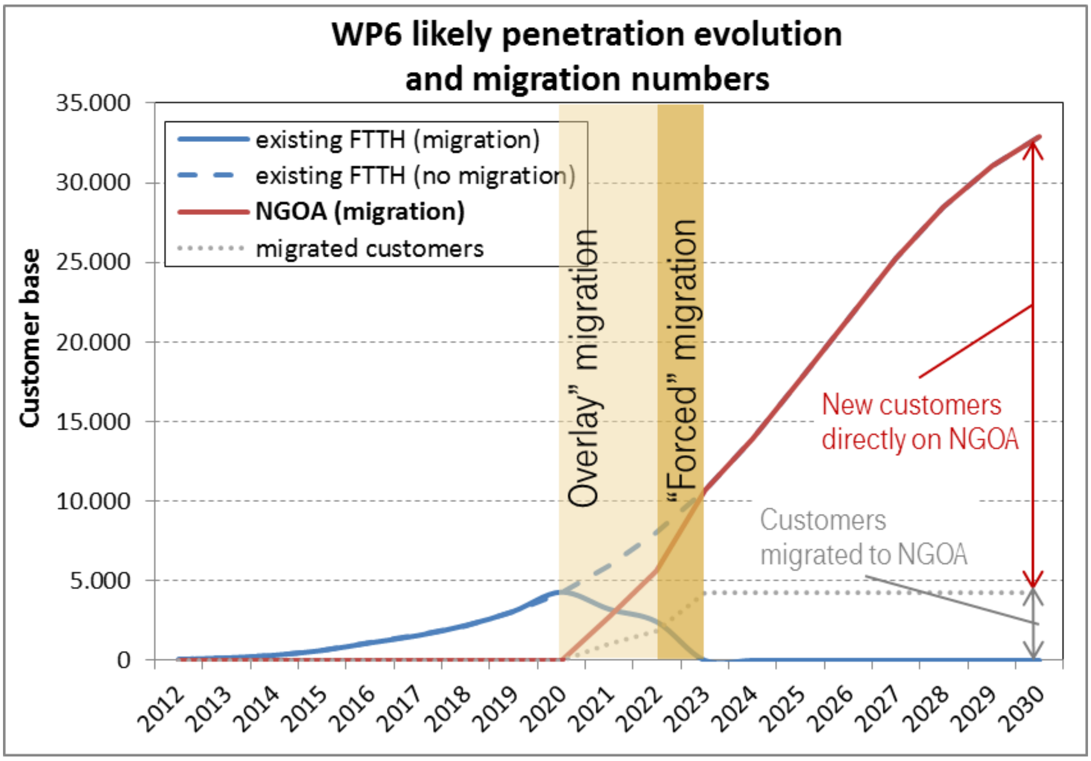


Figure 25 WP6 likely penetration evolution and migration numbers

Beside migration specific network components, also operational processes will be influenced. Migration specific operational effort is for instance required for fault management and maintenance of migration specific network components, additional footprint for migration specific network operations, and additional power supply cost for parallel operation of "old" and "new" platform. Costs for IT and process adaptations for migration as well as migration planning are assumed to be similar in all scenarios (considered as fixed cost block in the TCO model). Note: OPEX of the "old" FTTH architecture from 2012 - 2019 has not been considered because it is assumed to be nearly the same in all scenarios.

In a sensitivity study, the impacts of varied migration time frames and migration start years have been investigated. The results can be summarised that a variation in the width of the migration time frame window has a negligible impact on the TCO; whereas a delay of the actual migration start time would lead to a significant TCO increase, although it has to be combined with the revenues expected from the migrated customers.

4.2. Cost assessment analysis

This section presents what is included in the cost comparison of the different NGOA architectures for the three areas in the non-node consolidation and aggressive consolidation scenarios, presented in next section.

Table 3 TCO cost in 2010 for the different scenarios

	Non node consolidation			Future aggressive node consolidation		
	DU	U	R	DU	U	R
GPON 1:32	162.423	175.428	92.465	462.860	1.034.734	996.773
XGPON 1:32	162.745	175.567	92.537	463.823	1035588	997.544
AON p2p	175.647	181.830	95.646	500.981	1073216	1.031.421
AON AS	179.633	186.503	97.444	517.623	1.099.962	1.046.943

The presented results consider that a traditional access network is running from 2010 to 2019 and hence, the entire ODN infrastructure is supposed to be done in 2010 (the total TCO values of this year, dominated by the ODN costs, are presented in Table 3). The higher cost values of aggregation node consolidation refer to the higher costs to cover the larger area when considering node consolidation (although it will take place in 2020). This work considers as traditional access networks GPON1:32, XGPON1:32 and AON. At 2020, the NGOA architecture starts to be deployed and a fast migration from traditional to NGOA is assumed. Hence, the NGOA costs are considered from 2020 to 2030.

The assumptions for these studies is that the sustainable bandwidth per user is 300 Mbps, , the user penetration curve is the "Likely" as shown in Figure 7, and the infrastructure is the "PIP Greenfield in 2010". All costs are given in cost units, which have been normalized with respect the GPON ONT cost.

For each area and node consolidation scenario, the following graphs are included in each case study:

- Total TCO in Cost Units (CU) for each architecture (summing all costs from 2020 to 2030). This graph distinguishes the CAPEX and OPEX contributions.

- Total CAPEX in cost units [CU] and CAPEX per users connected in 2030 [CU/user] gives for each architecture the sum of the non-discounted CAPEX which include:
  - PIP Infrastructure (PIP Infra) such as distribution fibre, distribution duct, installation costs, cabinet, etc.
  - PIP Equipment (PIP Equip) such as power splitters, wavelength splitters, etc.
  - In house infrastructure (In house Infra) such as in house cabling and its installation costs
  - CPE Equipment (CPE Equip) includes the ONT cost as well as its installation cost
  - Network Provider costs (NP) includes OLT and any active equipment in the field such as reach extenders, Ethernet switches, etc.
- Total OPEX in cost units [CU] and OPEX per user [CU/user] gives for each architecture the sum of the non-discounted OPEX which include:
  - Fault Management (FM) which is the fault management costs associated to the failures in any equipment and infrastructure expect the CPE.
  - Fault Management of the CPE (CPE FM)
  - Energy gives the energy cost of the power consumed by any equipment except the CPE
  - CPE Energy is the energy cost of the power consumed by the CPE
  - Service Provisioning (SP) is the cost associated to any physical installation, service connection and service disconnection required by the users.
  - Floor space includes the cost of the floor space required by the OLT at the operator premises as well as any active component required in the field.
- Non-discounted TCO [CU] gives the non-discounted TCO per year excluding the 2010 as previously mentioned.
- Discounted TCO [CU] gives for comparative reasons, the discounted TCO per year. In this study, 5% and 10% discount rates [7] have been considered for physical infrastructure and equipment respectively.
- Finally, the average TCO per connected user per year shows the average over the years 2020-2030 of the TCO per users, taking into account the users which are connected in each year (based on the penetration curve).

All graphs on the CAPEX and OPEX show the costs in a non-discounted manner. In this way, the real cost is shown as experienced in the given years. While this gives a very good view on when to expect which costs in both investments (CAPEX) as well as operations (OPEX), it gives no information on the relation between both in terms of a business case. Typically the weight of an investment on a business case will diminish with a later investment time due to the effect this cost has on the risk of the business case. A company would want a return at least equal to its Weighted Average Cost of Capital (WACC), which represents the percentage costs a company incurs for lending or freeing this amount of money. This has been taken into account in the discounted TCO.

For each scenario covered in Sections 4.3 and 4.4, a graph showing the average non discounted TCO per connected user per year is also given. In this case it reflects the undiscounted cost spread over all subscription years and this can be interpreted as the fee that a customer should be paying in order to have a break-even for the network infrastructure. A note of warning should be given with this though. The costs of the network represent actually only the costs for deploying an FTTH network up to the customer and providing the customer with a CPE to connect on this network. It does not take into account the additional costs required for providing services such as IPTV over this network, not from software and management point of view, nor from content point of view. It does also not take into account any costs for selling the services to the customer and marketing the network services. Taking both these notes into account, it could still prove very meaningful for an operator to get an idea of the cost-portion to spend per subscription for the network side. Operators will have a means of comparing to more detailed cost figures enabling them to find out whether deploying and maintaining such NGOA network could be more profitable than the current network infrastructure.

Still one additional note of advice will be required. The current presentation of the costs on a per subscription base are calculated without taking discounting into account. As most of the costs are probably incurred during the first year, this will be almost the same as the discounted costs per subscription. Taking discounting into account, this does not directly translate into the subscription rate, as this subscription rate should be taking the same discounting into account as well. In order to get a view on the subscription price to charge in order to get a positive NPV, the following formula should be used:

$$NPV = \sum_{n \in years} \frac{CF_n}{(1+i)^n}$$

With NPV = total calculated NPV
years = 0 .. planning horizon (here 0-20)
i = discount rate (often the same as WACC)
CF = cash flow for a given year

We want to know how much a customer subscription should generate to get break even (considering the given discount rate of course). This means that we should change NPV by the NPV per subscription year. We should cover the costs which are now the only component in the cash flows by constant revenue flows (CRF) per customer subscription year (CRF later). This makes the formula into the formula below:

$$\sum_{n \in years} \frac{CRF_n}{(1+i)^n} = NPV/cust = \sum_{n \in years} \frac{CF_n}{(1+i)^n} \Big/ cust$$

The first term comes as a result from TONIC and we are interested in the value of CRF in the first term. We will work with this in the further analysis:

$$\sum_{n \in years} \frac{CRF}{(1+i)^n} = \frac{NPV}{cust}$$

$$CRF \sum_{n \in years} \frac{1}{(1+i)^n} = \frac{NPV}{cust}$$

This last term can be reduced analytically (is the sum of a geometric series) into

$$a + ar + ar^2 + ar^3 + \cdots + ar^{n-1} = \sum_{k=0}^{n-1} ar^k = a\,\frac{1-r^n}{1-r},$$

In which a = 1, $r = (1+i)^{-1}$ and the years are running from 0 till 19 (inclusive)

$$\sum_{n=0}^{19} \frac{1}{(1+i)^n} = \frac{1 - \frac{1}{(1+i)^{20}}}{1 - \frac{1}{(1+i)}} = \frac{(1+i)^{20} - 1}{i.(1+i)^{19}}$$

This is a value which can be calculated analytically upfront and is the cumulative discounted (CD) constant cost factor for the given amount of years. We replace this factor with CD later in the formula, rendering:

$$\begin{aligned} CRF * CD &= NPV/cust \\ CRF &= NPV/(cust * CD) \end{aligned}$$

4.3. NGOA Cost assessment: Non-node consolidation

This section presents the cost comparison of the different architectures for Dense Urban and Rural areas, which are the extreme scenarios. The comparative graphs in urban areas can be found in the Appendix.

4.3.1. Dense Urban area

As first cost comparison, we present the non discounted TCO for the NGOA operational time from 2020 to 2030. All NGOAs are evaluated considering as existing access solution GPON 1:32 except the AON point to point (P2P), which is kept as it is because is able to deliver the requested sustainable 300Mbps to the users, and the XGPON. It can be observed, that the TCO (given in Cost Units [CU] which are normalized to the GPON ONT cost) is lower for GPON and AON solutions, and higher for WSWDM PON and UDWDM PON solutions. The distribution in terms of CAPEX and OPEX is shown in blue and red respectively. In all cases, due to the fact that we are looking into the brownfield scenario, the OPEX cost contribution is higher than the CAPEX one.

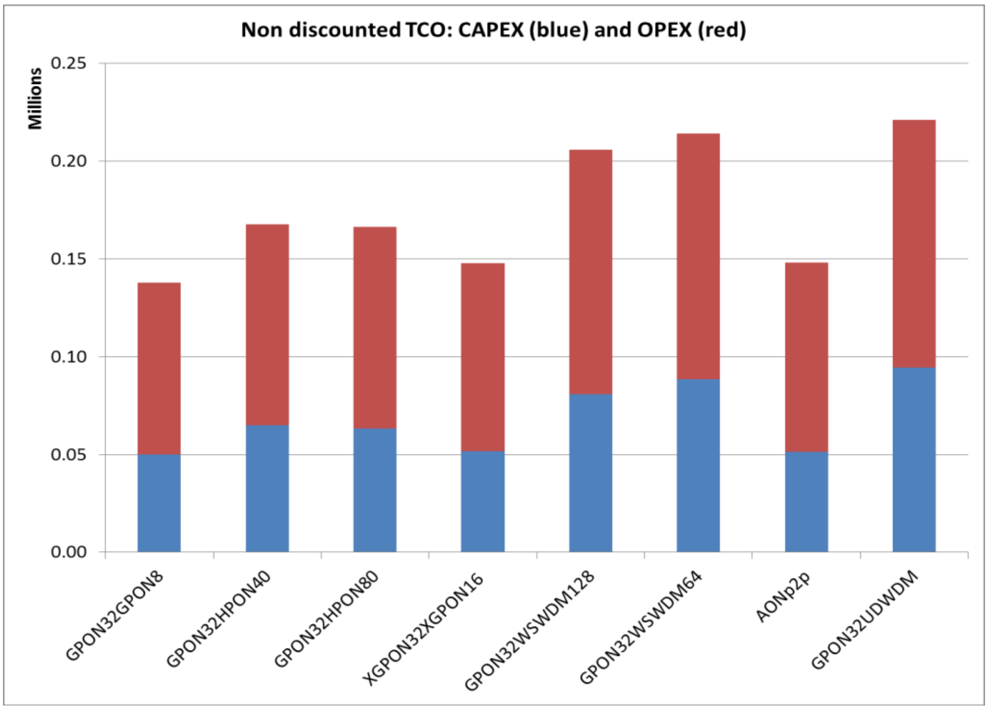


Figure 26 Non discounted TCO in DU area

In order to have an insight view of the cost factors, Figure 27 shows the total CAPEX (left axis) and CAPEX per user (right axis) distribution, whereas Figure 28 shows the total OPEX (left axis) and OPEX per user (right axis) distribution. The CAPEX distribution indicates that the CPE Equipment is an important cost factor for almost all architectures (except AON and GPON which uses existing technology whose cost has already decreased due to long time deployment). The In house infrastructure is the same for all the architectures. The NP cost which is mainly the OLT equipment, is significantly high for UDWDM and WSWDM PON solutions due to the high number of required cards and their cost. Furthermore, some architectures which need to upgrade their ODN, need also some extra PIP equipment in terms of power splitters and AWGs.

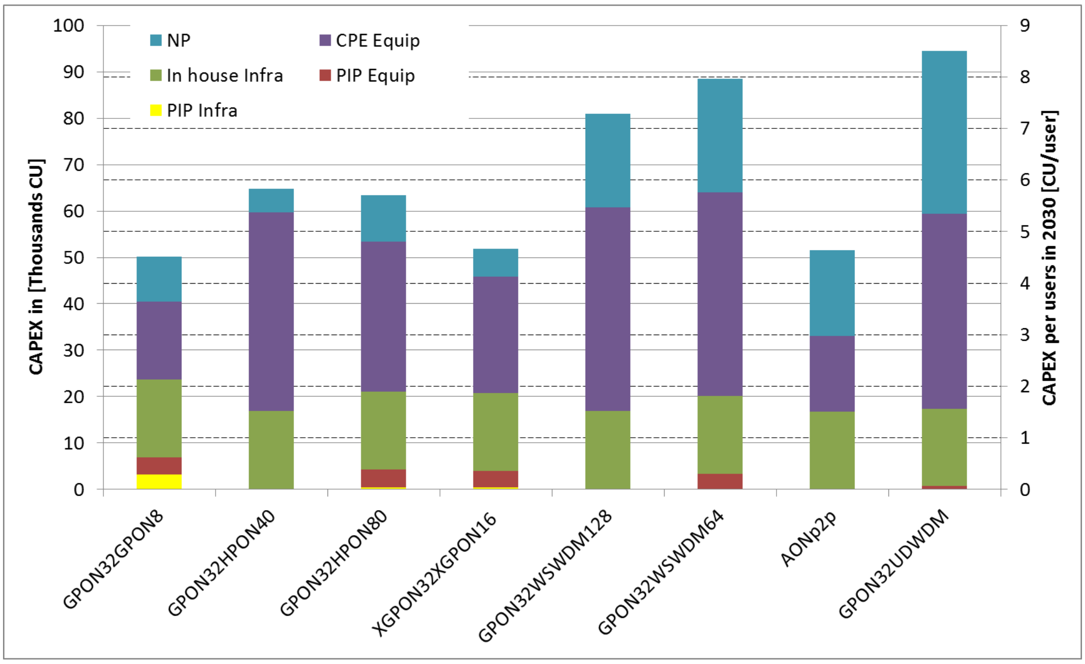


Figure 27 Total CAPEX [CU] on the left axis and CAPEX per user [CU/user] on the right axis of different NGOAs in Dense Urban area with non-node consolidation

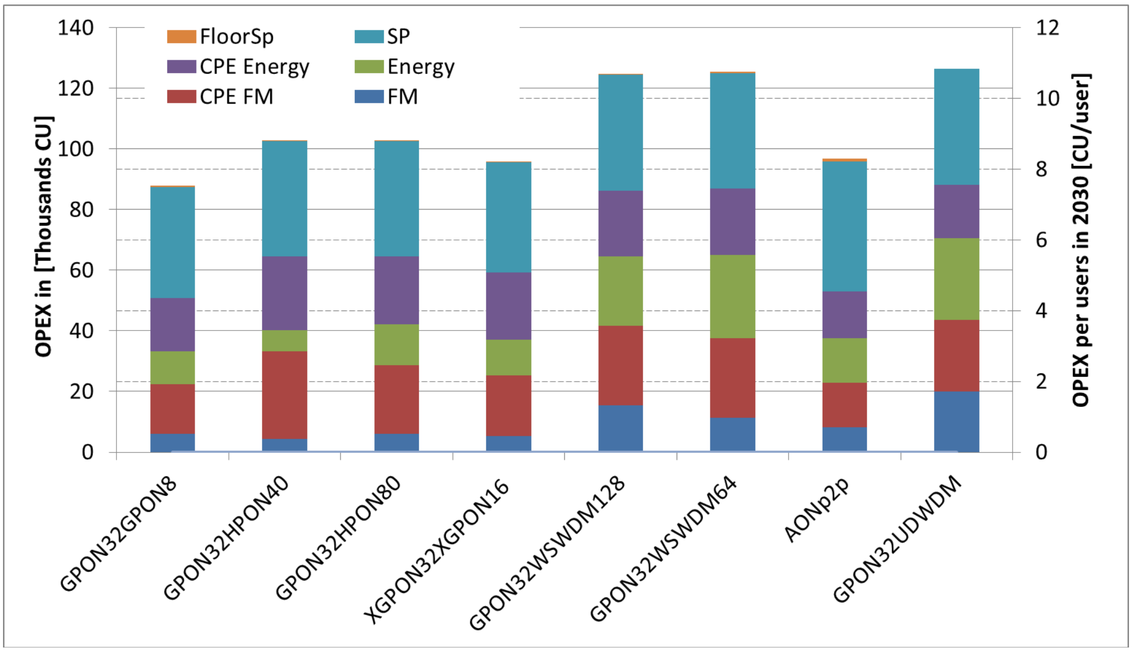


Figure 28 Total OPEX [CU] (left axis) and OPEX per user (right axis) in Dense Urban areas with non-node consolidation

The OPEX distribution shows that the service provisioning is an important cost factor for all architectures (slightly higher for AON P2P due to the manual patching of the new subscribers). Fault Management differs significantly among the architectures mainly due to the OLT failures (depending on the number of LT cards and their failure rate). The fault management cost of the CPE is significantly higher for the HPON40 solution, which uses APD receivers and hence has higher failure rate than simpler CPEs. Another differentiating parameter is the energy cost associated to the power consumed by the OLT and any required active component in the field. It can be observed that UDWDM and WS WDMPON have significantly higher power consumption than the other architectures.

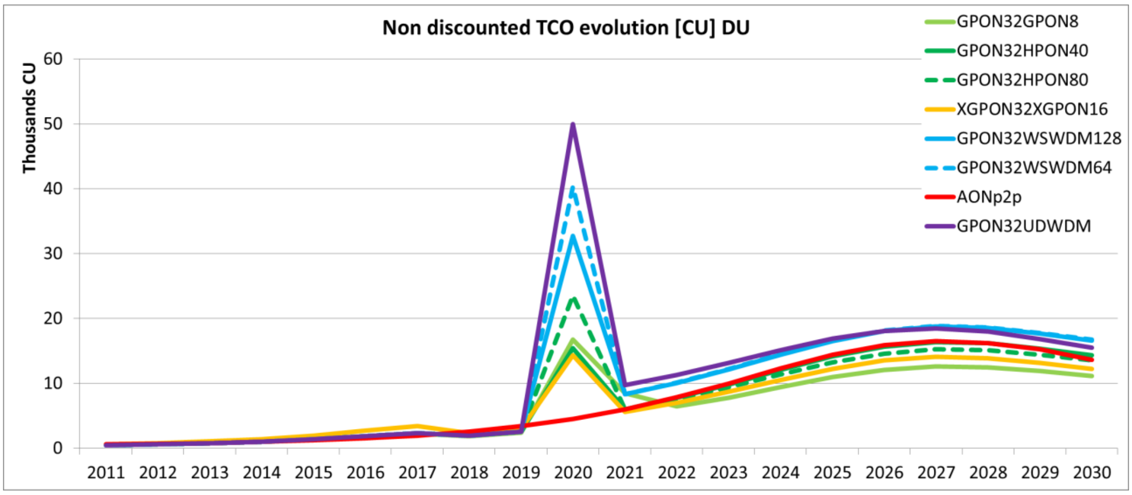


Figure 29 Non discounted TCO [CU] per year in DU areas with non-node consolidation

Furthermore, the non-discounted and discounted yearly evolution of the TCO has been depicted in Figure 29 and Figure 30 respectively. As mentioned previously, the TCO of year 2010 is high due to the required initial investment and has been included in Table 3. These figures show an important cost peak in 2020 which refers to the investment required to migrate to NGOA architectures. This peak does not appear for the AON P2P since no migration is required. The architecture requiring most of the investment is the UDWDM solution followed by the WS WDM PON architecture. The impact of the discount factors (10% for infrastructure and 5% for equipment) can be observed as an important decrease of the TCO and a decrease of the relative differences among the architectures (especially after the migration).

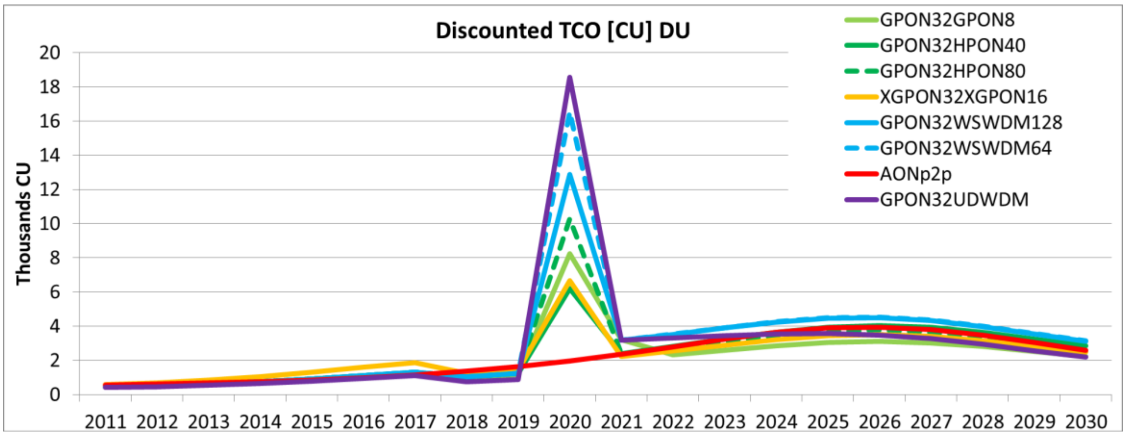


Figure 30 Discounted TCO [CU] per year in DU areas with non-node consolidation

In order to have a better understanding of the TCO distribution per connected user, Figure 31 presents the average TCO per year per connected user with the most important CAPEX and OPEX parameters. It can be observed that the AON P2P has the lowest TCO per user since it is not a migration, but just a progressive extension of the network based on the penetration rate. As expected the CPE cost is the most important factor since it is not shared among the users.

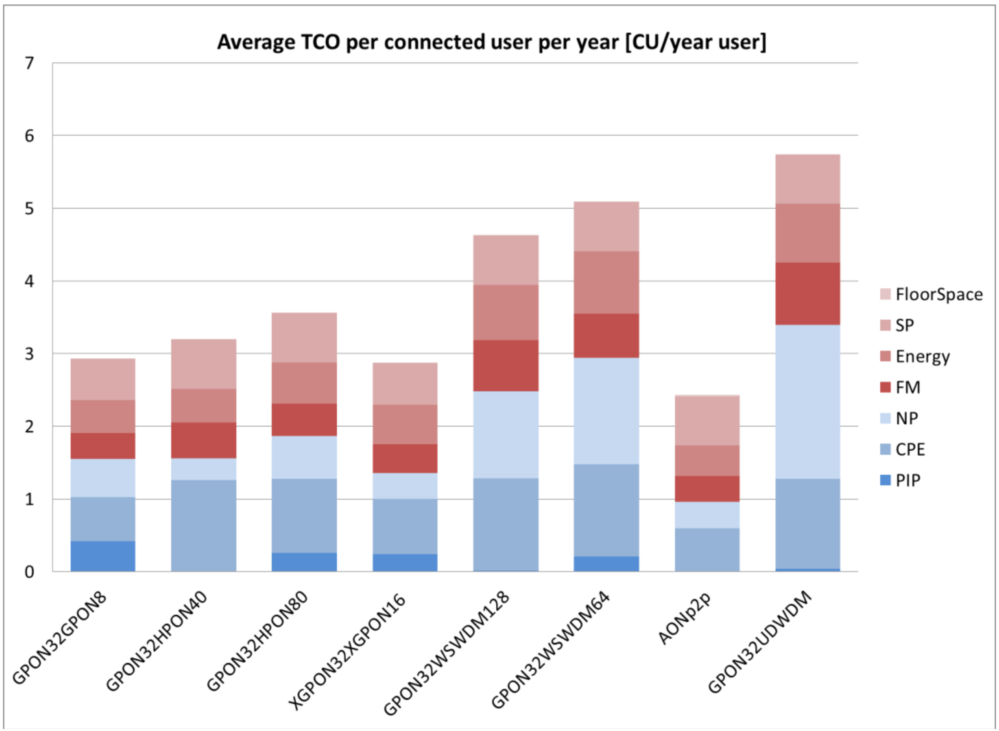


Figure 31 Average non discounted TCO (CAPEX components in blue and OPEX components in red) per connected user per year in DU areas

4.3.2. Rural area

The first graph shows the total non discounted TCO for the different architectures from 2020 to 2030. It can be observed that the TCO is lower than in dense urban areas (Figure 26) due to the fact that the number of users is less and the most costly aspect of rural areas, which is the ODN, is not included since we are looking into the brownfield scenario. The dominance of OPEX over CAPEX is kept also in rural areas.

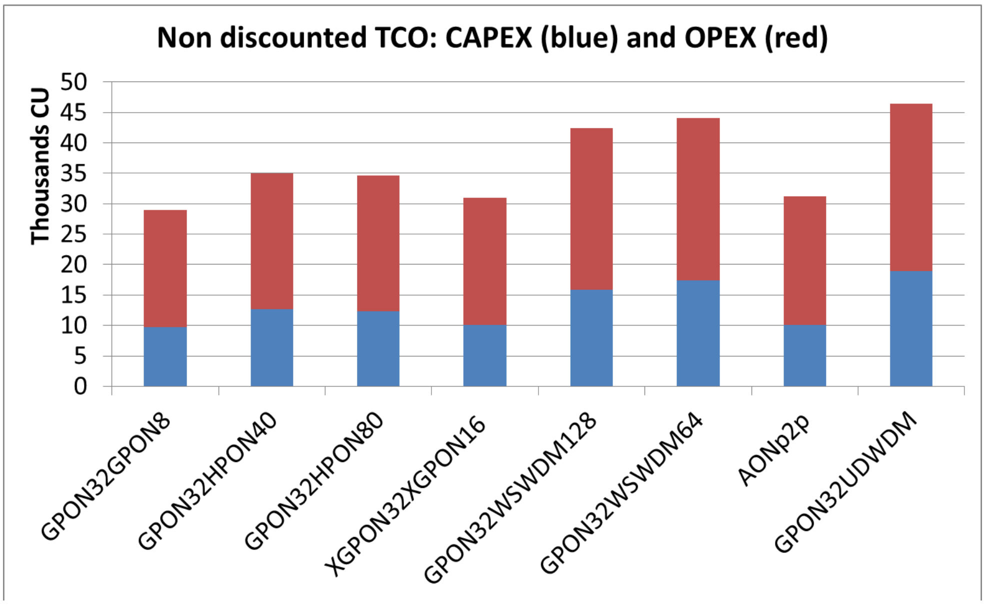


Figure 32 Non discounted TCO in rural area

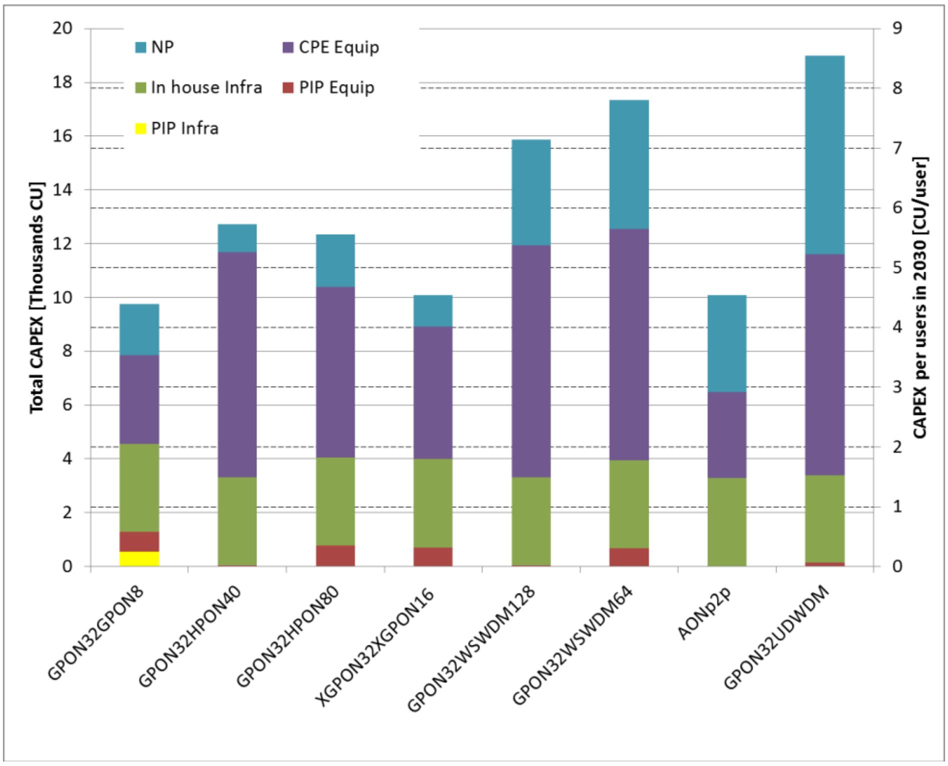


Figure 33 CAPEX [CU] on the left axis and CAPEX per user [CU/user] on the right axis of different NGOAs in rural areas with non-node consolidation

The CAPEX distribution (shown in Figure 33) has the same behavior as for dense urban areas (Figure 27) but with lower cost (around one fifth compared with the dense urban area). However, the cost per user is comparable in both areas since we are looking at the brownfield scenario that considers an existing ODN, which impacts the cost per user as shown in Section 4.2. The same applies for the OPEX distribution (shown in Figure 34): lower OPEX behaviors than dense urban areas, but comparable OPEX per user.

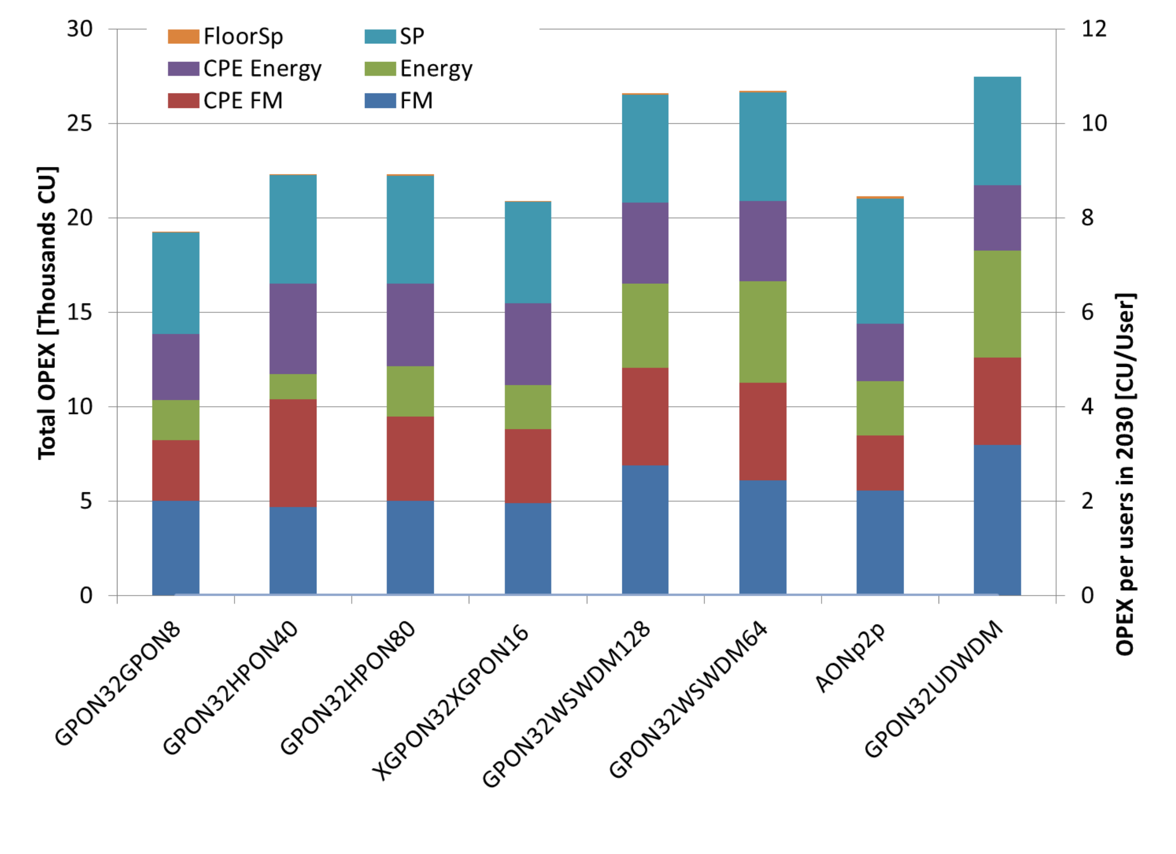


Figure 34 Total OPEX [CU] (left axis) and OPEX per user (right axis) in rural areas with non-node consolidation

The non discounted and discounted TCO yearly evolutions shown in Figure 35 and Figure 36 respectively, reveal the same evolution as for the urban area. UDWDM and WS WDM PON architecture keep being the architecture requiring the highest investment at the migration. AON P2P keeps the increasing investment curve based on the penetration curve.
The average TCO per connected user and year, shown in Figure 37, highlights in red the OPEX and in blue the CAPEX aspects that influence the average TCO. It can be observed that the behaviors and relative differences among the architectures are the same as in dense urban areas, just showing a slight increase in rural areas.

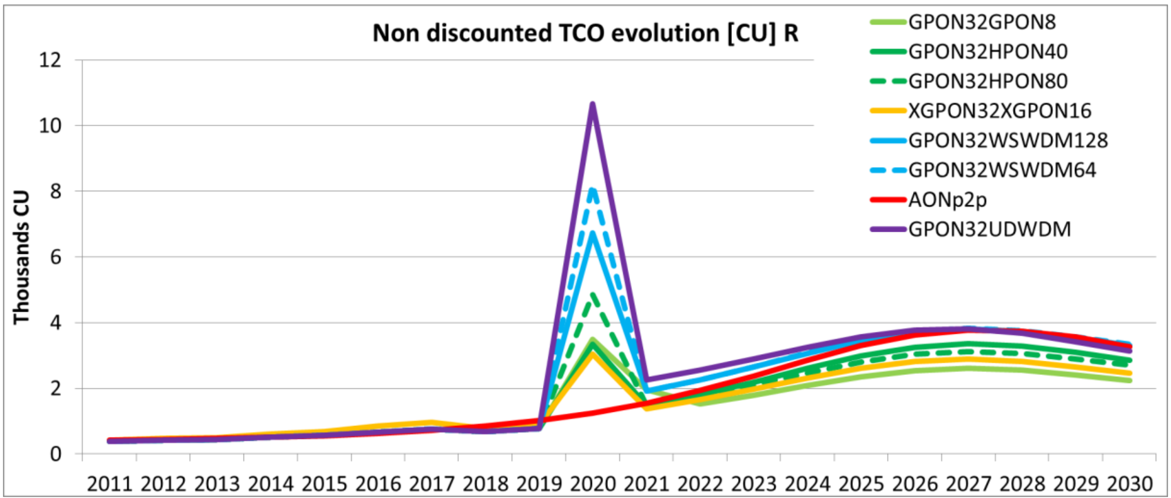


Figure 35 TCO [CU] per year in rural areas with non-node consolidation

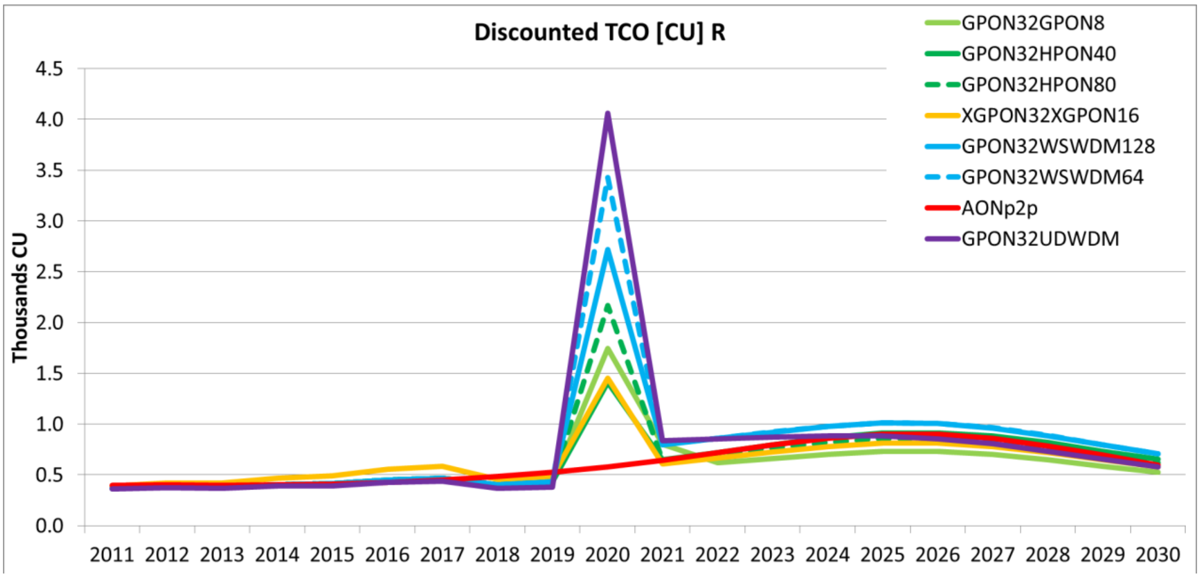


Figure 36 Discounted TCO [CU] in rural areas with non-node consolidation

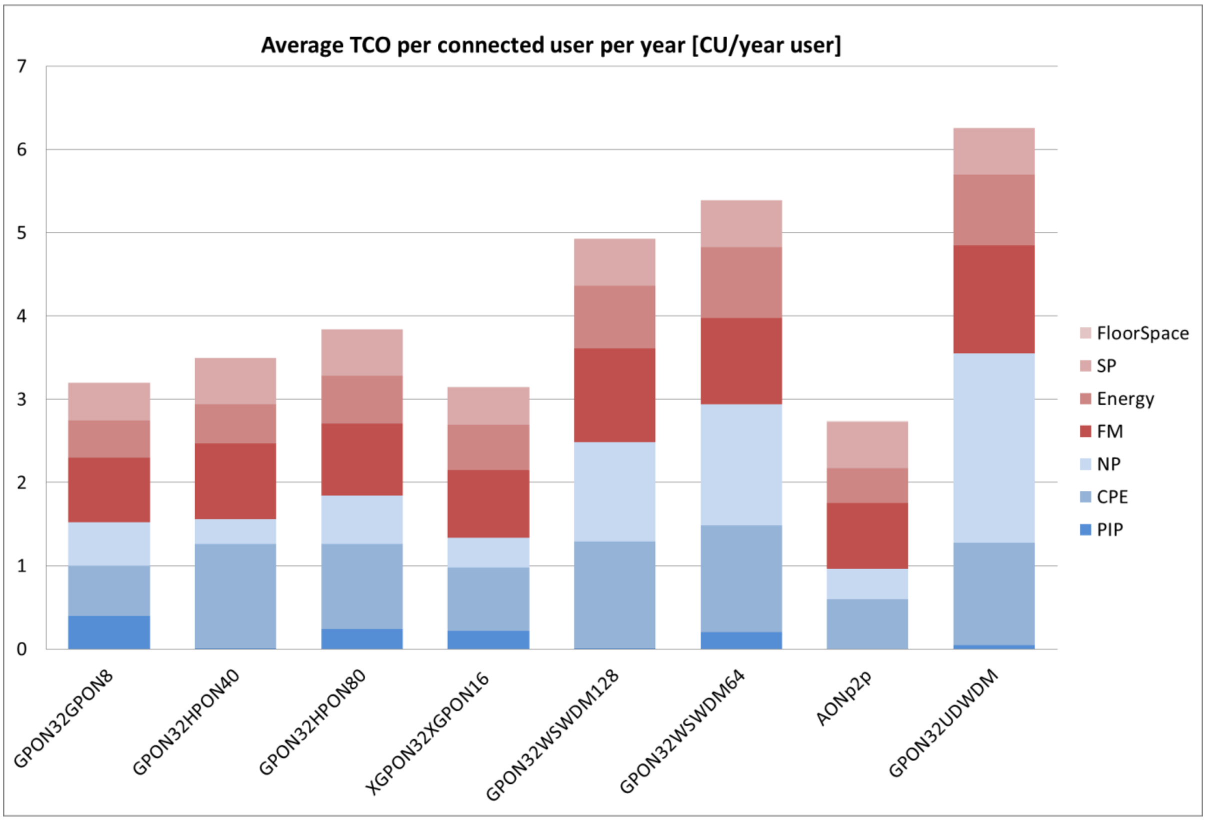


Figure 37 Average non discounted TCO (CAPEX components in blue and OPEX components in red) per connected user per year in rural areas

4.4. NGOA Cost assessment: Aggressive node consolidation

Aggressive node consolidation considers an important reduction of the number of central offices where OLTs are kept, reducing also the cost of the required aggregation network. In this scenario, the OLTs are installed at PCP6 (metro access node) and only requires Aggregation network I (presented in Section 2.3 in this document).

In this section several solutions are presented: some solutions correspond to migration from traditional optical access networks (e.g. GPON or active star AS) to NGOA architectures, whereas other solutions relate to the upgrade of the traditional optical access networks by reducing their splitting ratio and increase the number of optical fibres required from PCP5 to PCP6.

In case of NGOA migration, the new systems will directly be installed at the consolidated PCP6 locations from 2020 on, whereas a forced node consolidation in the GPON reference scenario would require additional efforts for moving or re-invest the existing GPON OLTs including network re-configurations. Those efforts have not been considered monetary, because it can be assumed, that from 2020 new GPON OLTs for demand increase will only be installed at the consolidated location, whereas the existing GPON OLTs in the traditional CO will be smoothly phased out till 2030, without moving them to the consolidated locations.

4.4.1. Dense Urban area

Let first compare in Figure 38, the TCO of the different solutions. It can be observed that OPEX keeps being more dominant than CAPEX. Furthermore, UDWDM is still the most costly architecture followed by WS WDM and WR WDM PON solutions. The lowest cost architectures are the upgrade of XGPON1:32 (just adding LL5 link), AS AON WDM Backhauled (just adding backhauling part for existing active star), the upgrades of GPON and XGPON (by reducing the splitting ratio) and the migration towards HPON.

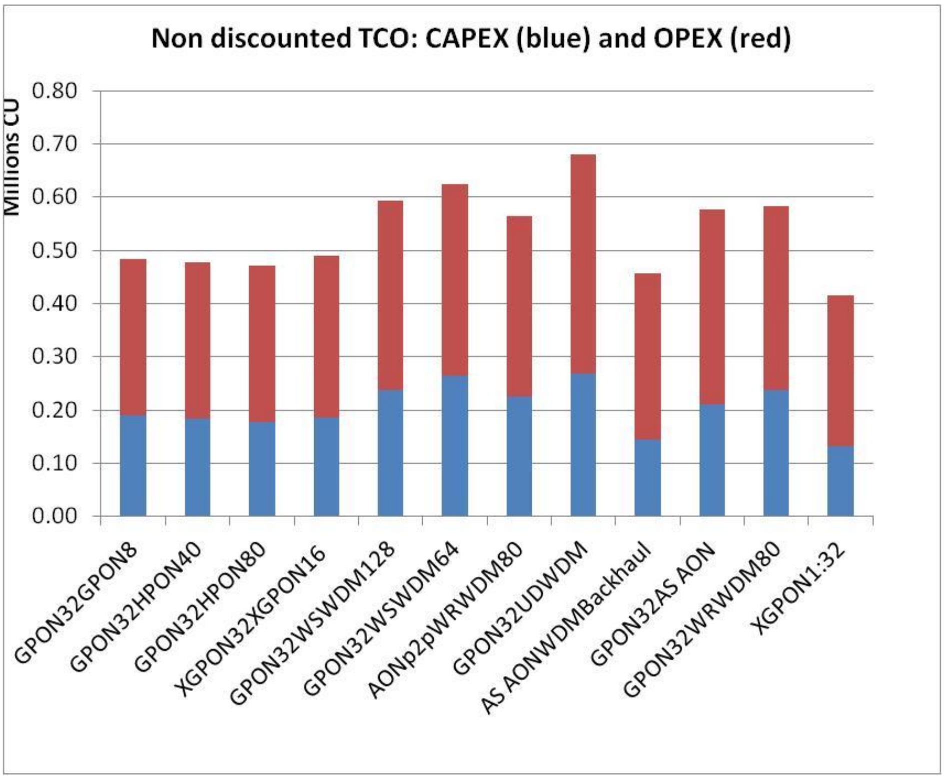


Figure 38 Non discounted TCO in DU with aggressive node consolidation

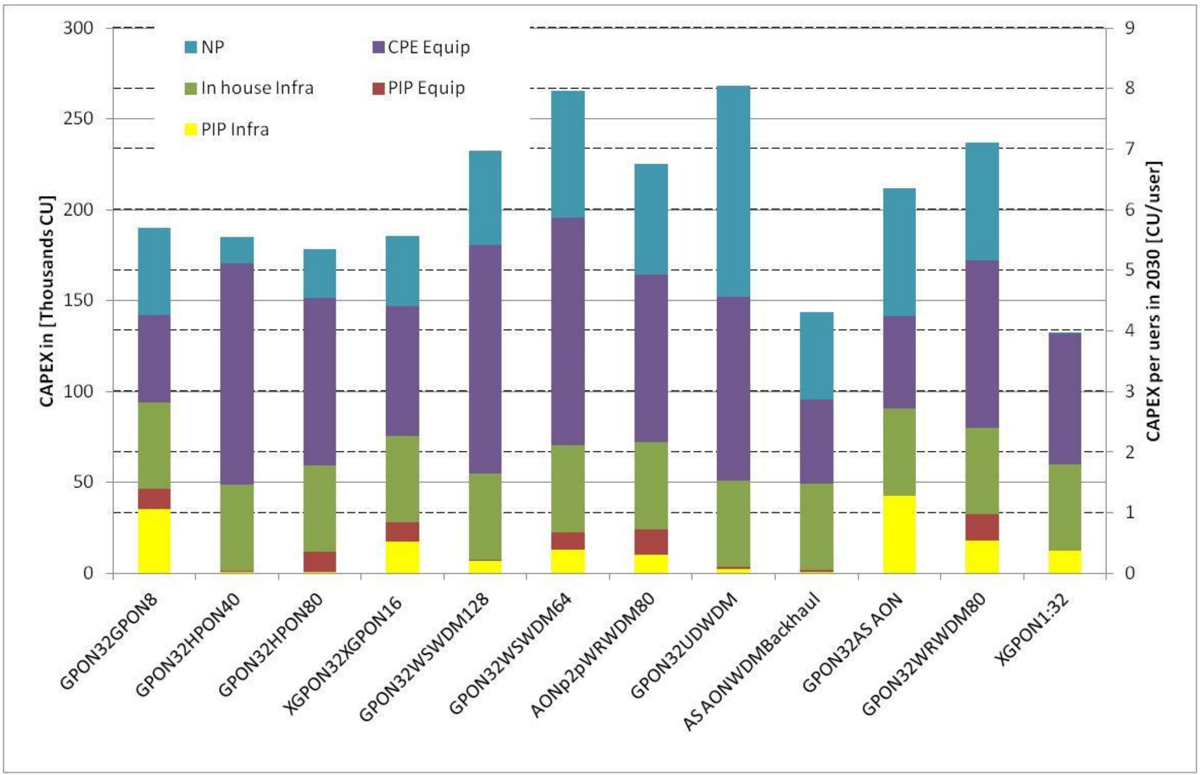


Figure 39 CAPEX [CU] on the left axis and CAPEX per user [CU/user] on the right axis of different NGOAs in dense urban areas with aggressive node consolidation

Figure 39 presents the CAPEX distribution in terms on equipment and infrastructure components. It can be observed that the NP equipment is significantly high for UDWDM, WS WDM and WR WDM PON solutions. Furthermore, it can be observed the high impact that CPE equipment has in HPON40, WS WDM PON solutions which require APD ONTs. In this aggressive consolidation scenario, some solutions require significant investments on PIP equipment (e.g. AWGs, splitters) such as the GPON upgrade to 1:8 since it needs to replace all the 1:32 splitters by 1:8 splitters; or PIP infrastructure such as the upgrade of GPON which due to the increase of number of splitters, more distribution fibre is required between PCP5 and PCP4s. GPON migration to active star AON is associated with a large increase in the PIP Infrastructure cost due to the need to install active cabinets.

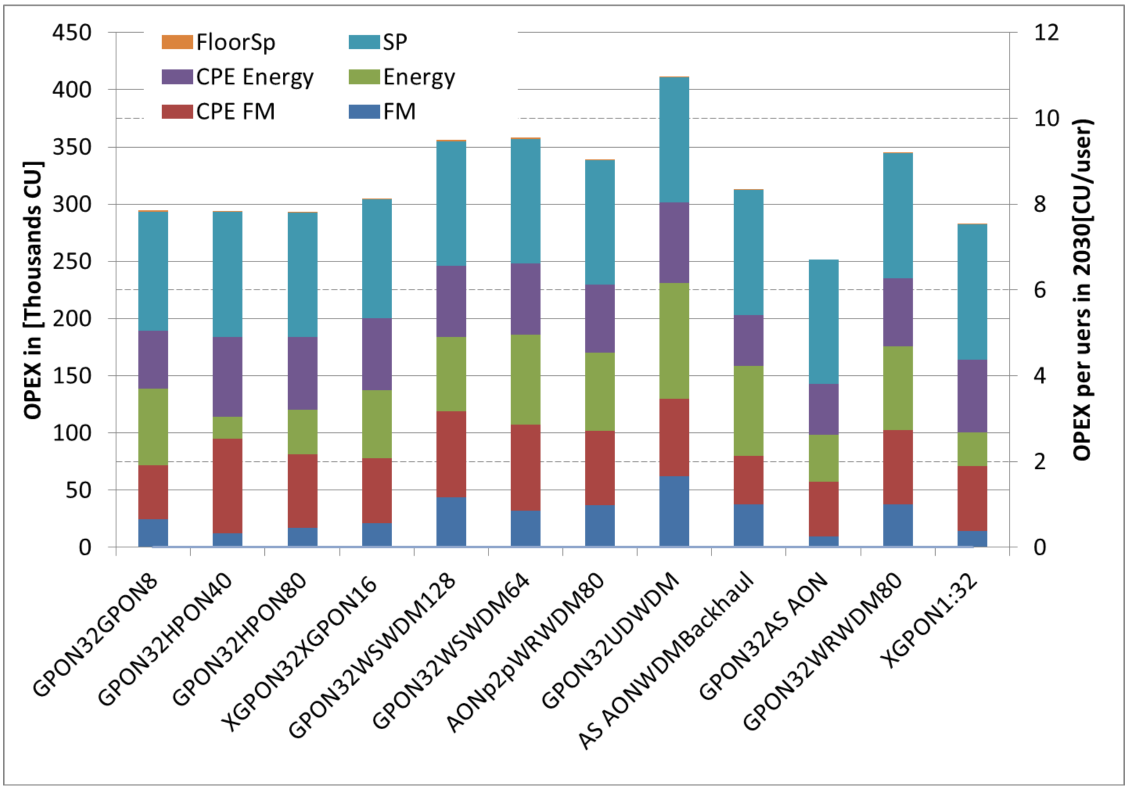


Figure 40 OPEX [CU] (left axis) and OPEX per user [CU/user] (right axis) of different NGOA solutions in dense urban areas with aggressive node consolidation

When comparing operational costs, as shown in Figure 40, we can observe that an important difference is the power consumption, which is significantly reduced by HPON 40 but predominant in UDWDM and GPON AS AON migration. The CPE Fault Management (FM) is an important cost factor for all the architectures: HPON40 ONT and WS WDM ONTs have higher failure rates than GPON and AON ONTs. The FM of PIP and NP is significant.

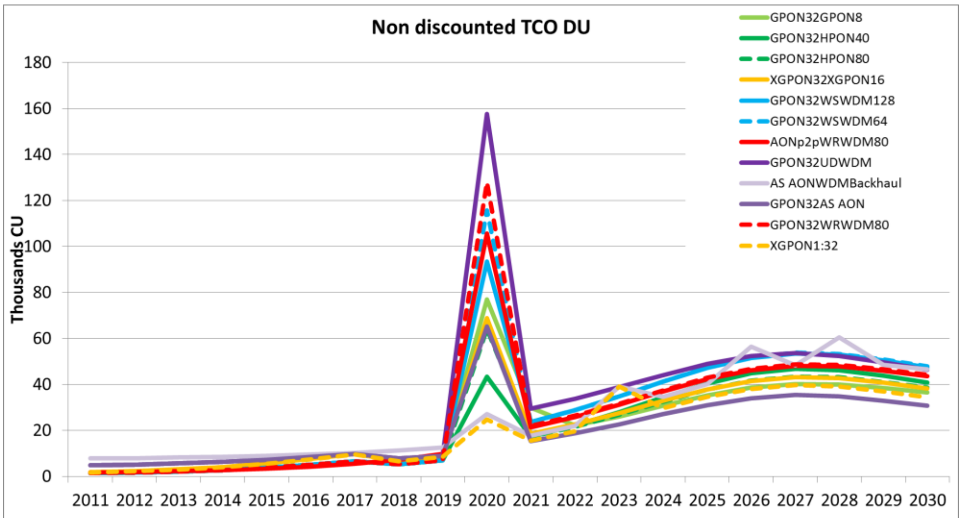


Figure 41 Non discounted TCO [CU] per year in DU areas aggressive consolidation scenario

Figure 41 shows the total cost per year for the different architectures. It can be observed that for existing networks, UDWDM and AON star have higher cost than the possible counter technologies. In 2020 the necessary investment required to migrate towards NGOA which includes infrastructure and equipment is shown: UDWDM and WR WDM PON require the highest investments, whereas active solutions and XGPON upgrade have the lowest. In the following years, the total cost increases with the number of users (more users imply more

CPE, more SP costs, more energy consumption, more FM, etc.). Figure 42 shows the impact of the cost discount factors.

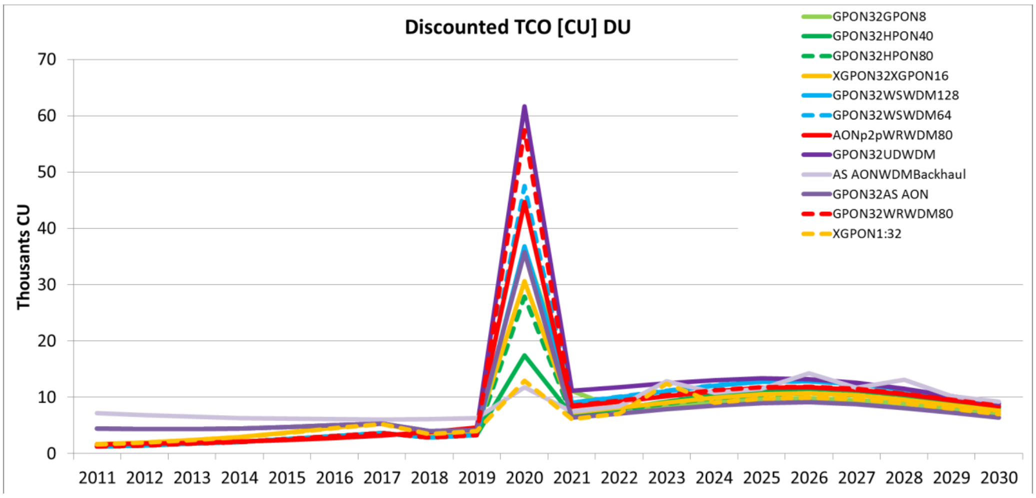


Figure 42 Discounted TCO [CU] per year in DU areas aggressive consolidation scenario

If we look at the non discounted cost per connected user of each year for each architecture, as shown in Figure 43, it can be observed that the CAPEX contribution is higher than the OPEX except for the AS AON WDM backhaul and XGPON. Furthermore, the impact of each cost parameter depends on the architecture: e.g. the cost of OLT equipment (NP) is much more important for the UDWDM than for the HPON architecture; the PIP infrastructure for the GPON upgrade is much higher than the PIP infrastructure required for the AS AON WDM Backhaul.

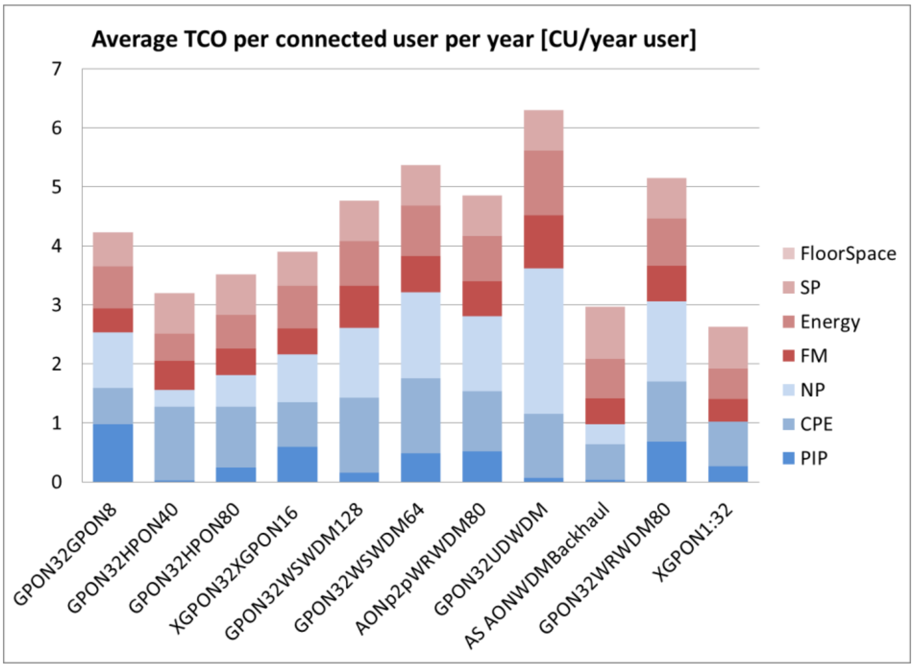


Figure 43 Average non discounted TCO per connected user per year

4.4.2. Rural area

Figure 44 shows the total non discounted TCO in rural areas, which shows a different profile than in dense urban areas mainly due to the higher costs of upgrading traditional GPON and XGPON solutions. In these types of areas, WS WDM PON becomes a more expensive solution than UDWDM because of the significant reduction in LL5 costs that can be achieved through the higher fan-out of the ultra dense PON variant. The most cost efficient solutions are the HPON as well as the AS AON with WDM Backhaul: due to the high client count and the high reuse of existing infrastructure.

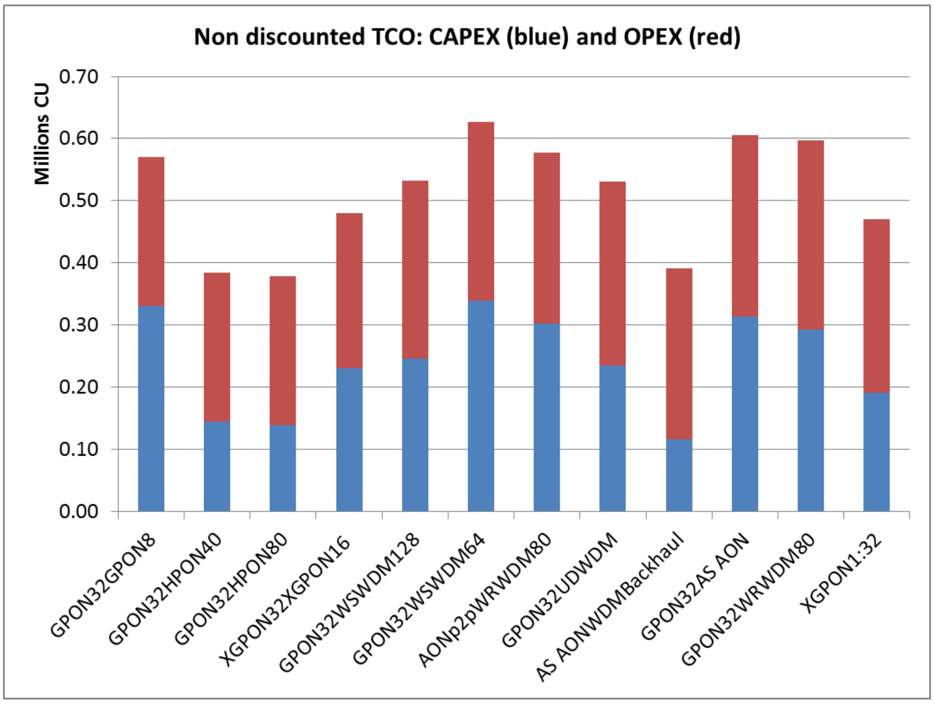


Figure 44 Non discounted TCO in rural areas with aggressive node consolidation

Figure 45 depicts the CAPEX distribution and the high impact that PIP infrastructure has on these types of areas with aggressive node consolidation can be observed: in particular, the LL5 required to interconnect the traditional ODN with the new location of the OLT at PCP6. This LL5 cost is significantly high for GPON and XGPON due to the high number of splitters that should be now connected to the PCP6. Once again, we can observe high PIP Infra costs associated with the GPON to active star migration. While the LL5 cost is not excessively burdensome (it is similar to any PON variant with a 1:32 split), the cost of installation of active cabinets is also included, increasing the cost.
When comparing the OPEX distribution (shown in Figure 46), it can be observed that the FM is higher than for dense urban areas due to the longer infrastructure that should be maintained and repaired. Furthermore, the UDWDM OPEX is comparable to other solutions and not as high as in dense urban areas due to the high dependency with the number of users: in urban areas the total number of users is lower. The energy cost relative comparison with the other architectures is similar to the dense urban areas (except for the UDWDM as previously mentioned).

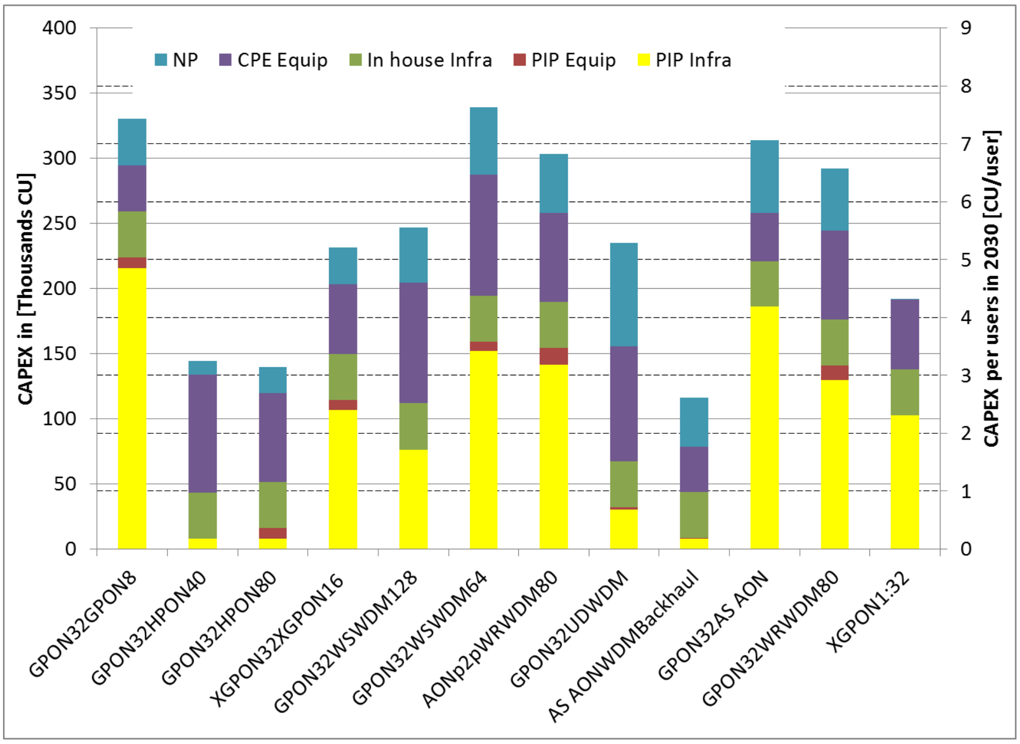


Figure 45 CAPEX [CU] on the left axis and CAPEX per user [CU/user] on the right axis of different NGOAs in rural areas with aggressive node consolidation

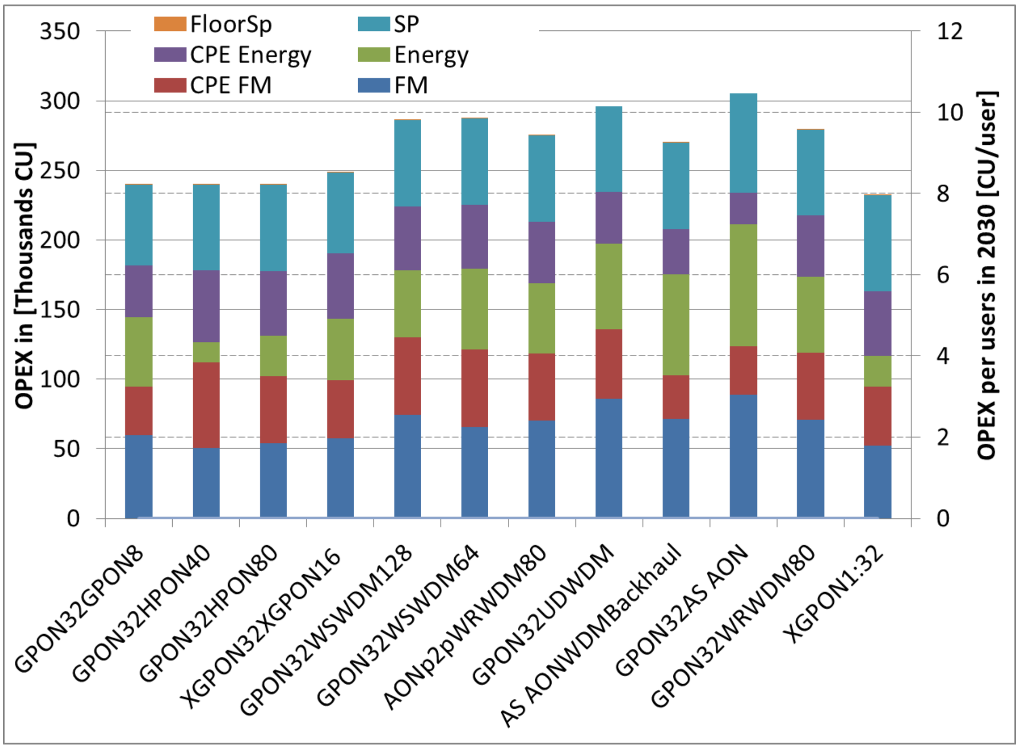


Figure 46 Total OPEX [CU] (left axis) and OPEX per user [CU/user] (right axis) of different NGOA solutions in rural areas with aggressive node consolidation scenario

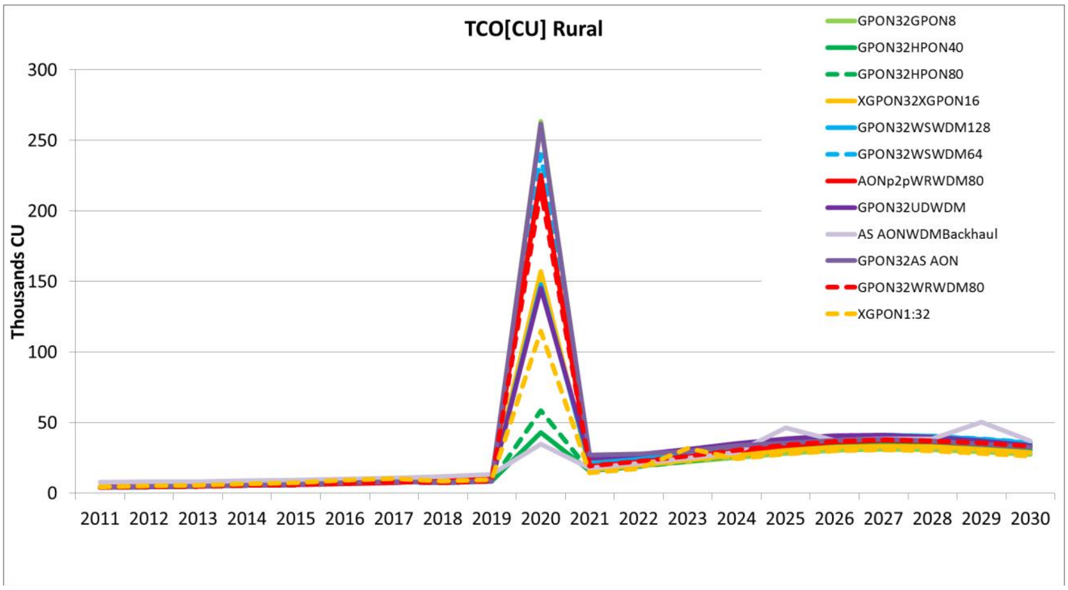


Figure 47 TCO [CU] per year in Rural areas with aggressive consolidation scenario

Figure 47 and Figure 48 show the non discounted and the discounted TCO yearly distribution, where the investment peak in the migration year 2020 can be clearly observed. However, in rural areas, the GPON upgrade from 1:32 to 1:8 becomes as expensive as the GPON to AS AON architecture and close to WR WDM (80 channels) and WS WDM (64 channels) solutions due to the high investments required in PIP Infrastructure. The peak cost of UDWDM drops to almost 50% of the aforementioned architectures.

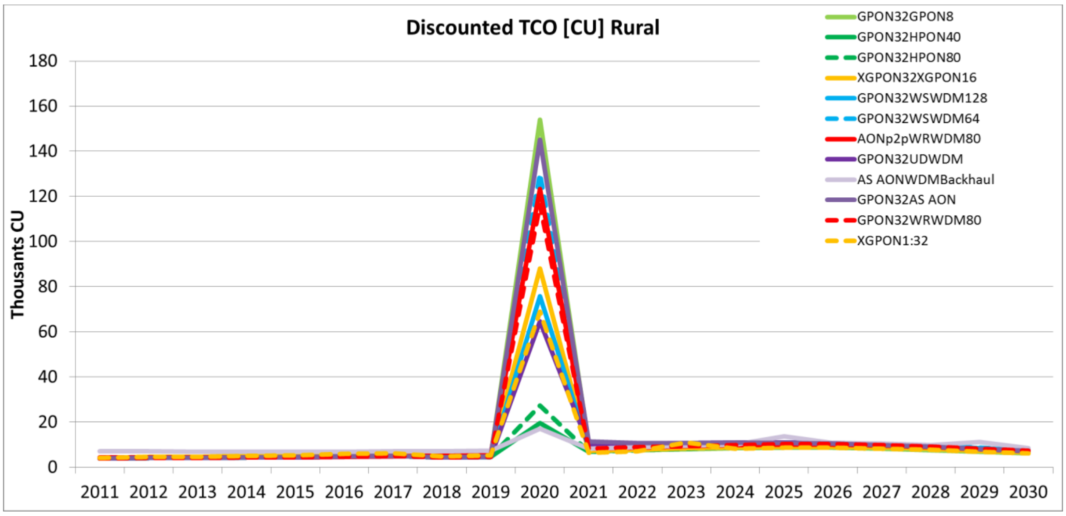


Figure 48 Discounted TCO [CU] in Rural areas with aggressive node consolidation

As last graph, Figure 49 shows the average non discounted cost per connected user per year and it can be confirmed that the least costly solutions are the HPON as well as the extension of AS AON with a WDM Backhaul. Other solutions increase the cost per user and year with 50% and even 150% as is the case of upgrading GPON.

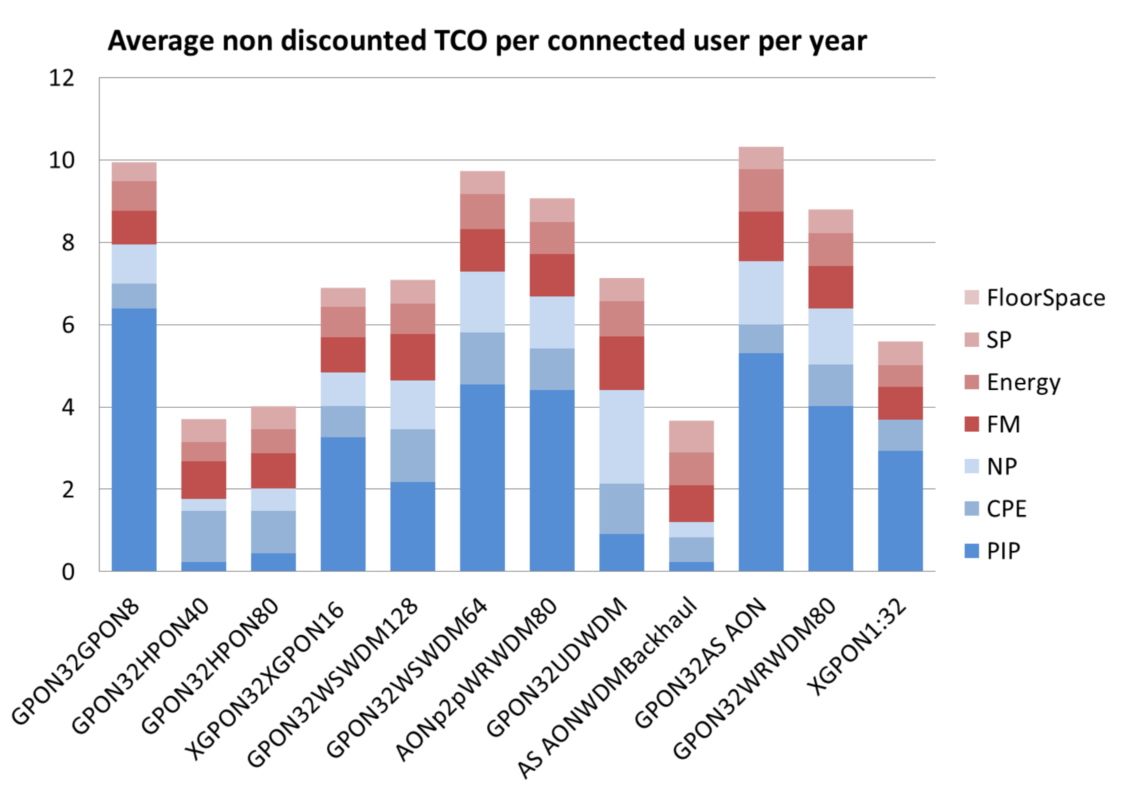


Figure 49 Average non discounted TCO per connected user per year for Rural areas

4.5. Non-node consolidation vs. aggressive node consolidation

This section introduces the cost comparison taking into account the aggregation cost. As presented in Section 2.3, the cost model is based on the node consolidation degree. For that reason, in order to have a fair comparison of different architectures, the cost of the aggregation network should be considered. This section presents the cost comparison (TCO sum from 2010 to 2030 considering consolidation in 2020) of two passive (HPON40 and WRWDM) and active solution with aggressive and non-node consolidation for the three types of areas: DU, U and R.

Figure 50 depicts the NP and aggregation cost per user for each scenario. It can be observed that the aggregation costs are significant in the rural area due to the lower sharing factor.

Figure 51 presents the losses/savings in [CU/user] that aggressive node consolidation has, when compared to the non-node consolidation:

- HPON40: when migrating from the non-node consolidated GPON to the node consolidated HPON40 architecture
- WR WDM: when migrating from non-node consolidated AON P2P to node consolidated WRWDM architecture
- AON WDM Backhaul: when migrating from non-node consolidated AON active star to node consolidated WDM backhaul architecture

It can be observed, that the migration towards HPON brings savings in any type of area, but significantly in rural areas, where the savings in terms of aggregation are more than 10CU/user. The NP equipment does not play any important role in terms of savings (0.2 CU/user).

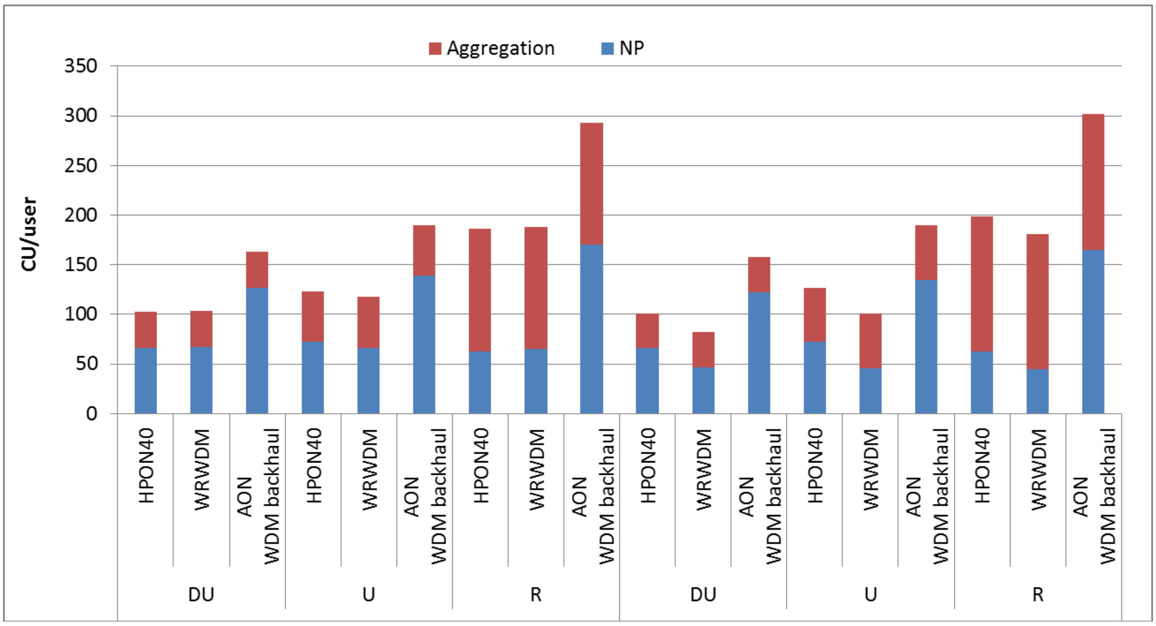


Figure 50 Access NP and aggregation cost per user [CU/user] for active and passive architectures with and without node consolidation

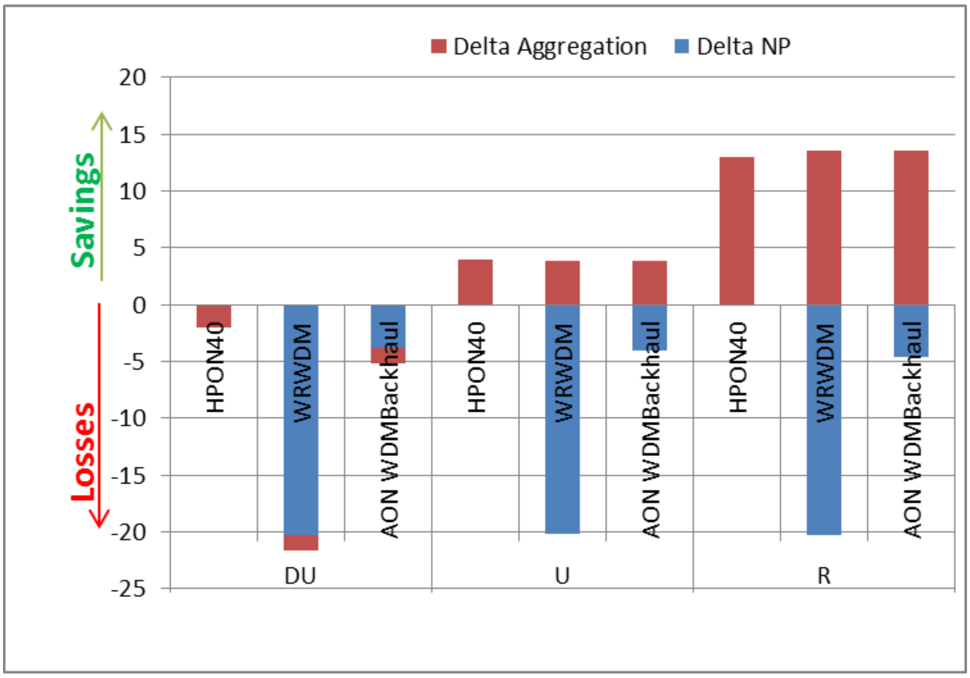


Figure 51 Cost per user [CU/user] savings when implementing node consolidation

When migrating from AON P2P to WRWDM PON architecture, it can be observed in Figure 51 that in a dense urban area node consolidation did not bring any cost saving for both access network and aggregation network. In urban and rural area, the benefit of node consolidation appears only for the aggregation network cost, and this benefit becomes considerable visible in rural area, however, the cost saving only affects the aggregation network cost, not the access network, and the cost saving from the aggregation network is not high enough to compensate the access network cost of the new investment for migration from AON P2P to the node consolidated WRWDM.

When migrating from a non-node consolidated AON active star to a node-consolidated WDM backhaul architecture, we can find in dense urban area there is no benefit from node consolidation, however for urban and rural areas, node consolidated WDM backhaul architecture start making cost savings for the aggregation networks. In rural area although there are add-on costs for the migration towards the new architecture on the access network part, the cost saving of aggregation network is large enough to cover the cost of the new architecture, therefore it is worth to do node consolidated migration for rural areas.

4.6. Impact of Feeder Fibre protection

As presented in Section 3.3.1, the feeder protection scheme applies only for the aggressive node consolidation scenario. The feeder part refers to the fibres between the local exchange office (PCP5) and Center Access Node (PCP6). Non-node consolidation architectures such as AON P2P only covers traditional access area till PCP5, therefore they don’t have feeder part as described above, and hence they are not included in this study. In this section the increase of CAPEX and OPEX is presented for each area and architecture. It has to be mentioned that the LL5 ducts are assumed to be available and hence, only LL5 cable and installation costs have been considered.

4.6.1. Dense Urban area

Let us first study which is the increase of CAPEX and OPEX due to the FF protection. Figure 52 presents the increase of CAPEX in terms of PIP equipment and infrastructure, CPE equipment, In-house infrastructure and NP equipment. It can be observed that FF protection requires significant NP investment as well as PIP infrastructure, especially for GPON and XGPON that require so many FF (thousands for DU areas). Figure 53 shows the increase of accumulated OPEX when offering FF protection. The increase is mainly due to Energy consumed by the OLT as well as the increase of Fault Management due to the failures at the protected FF as well as at the second OLT.
Furthermore, in order to see which is the extra cost on the TCO to offer protection, Figure 54 can be analysed: the blue bars show the TCO for the unprotected solution and the red bars show the extra cost required in order to offer FF protection. It can be observed that protected HPON40 requires the smallest investment and appears to be the less costly solution when offering FF protection.

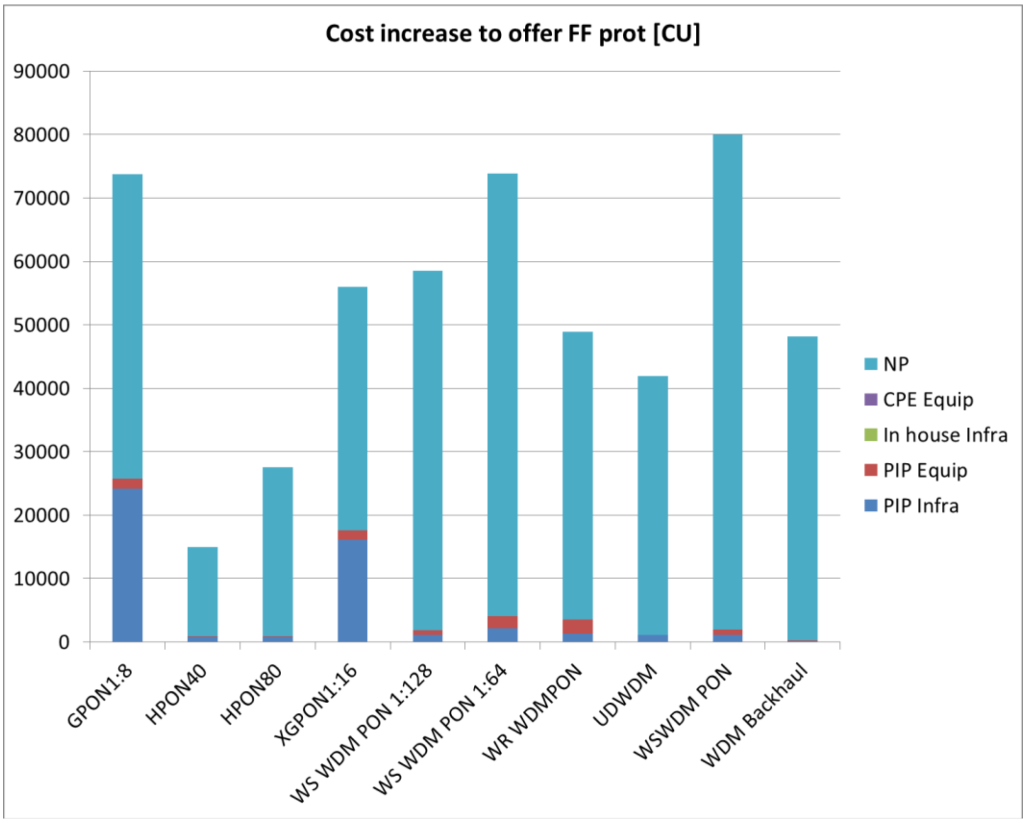


Figure 52 Increase of CAPEX when offering FF protection

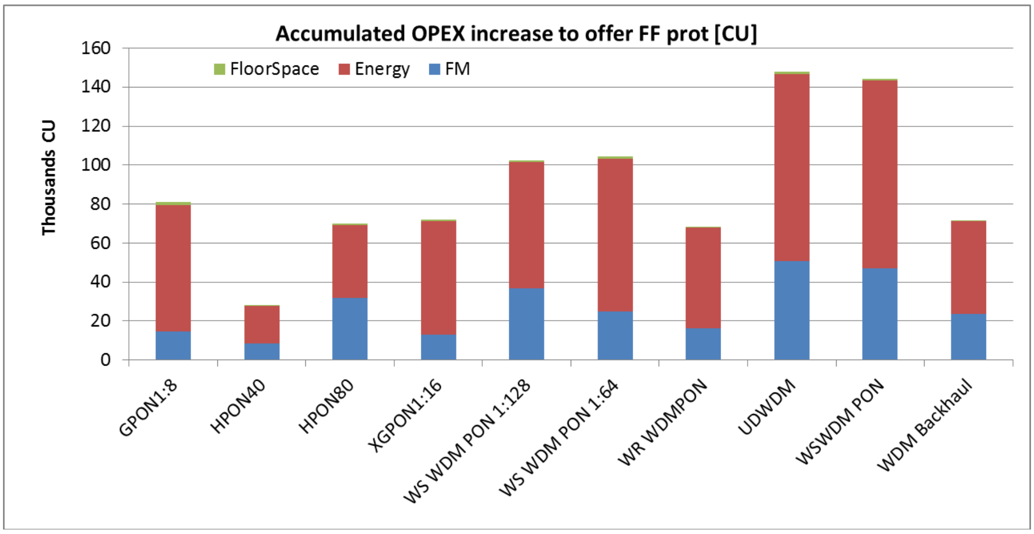


Figure 53 Increase of accumulated OPEX when offering FF protection

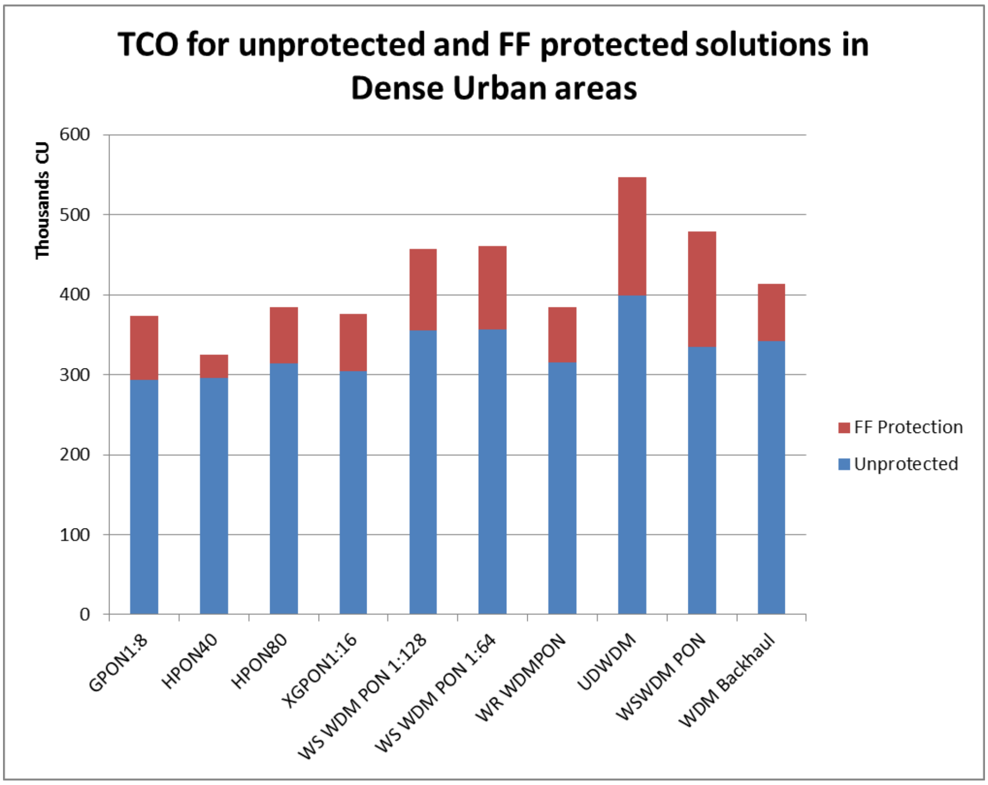


Figure 54 TCO for unprotected and FF protected solutions in DU areas

4.6.2. Rural area

In rural areas, the investment on infrastructure required by GPON and XGPON becomes the predominant CAPEX parameter and presents these architectures are the ones requiring the highest infrastructure investments. However, in terms of OPEX, UDWDM is still the most costly architecture due to its high power consumption and even more in the protection case which duplicates the OLT equipment.

When looking at the increase of TCO over the 10 operational years, as shown in Figure 57, it can be observed that the HPON40 solution is the most economical architecture offering FF protection. Although unprotected GPON had lower cost than HPON80 or WRWDM PONs, when protected, GPON turns to be more expensive than the other alternatives.

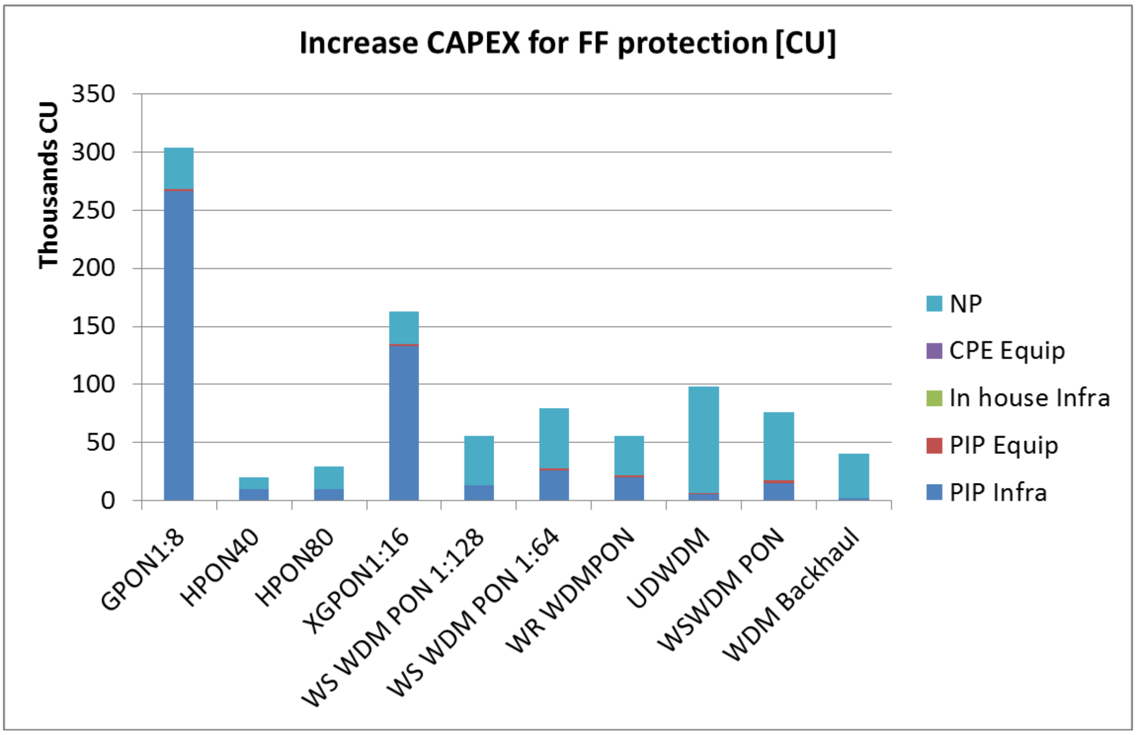


Figure 55 Increase of CAPEX when offering FF protection in Rural areas

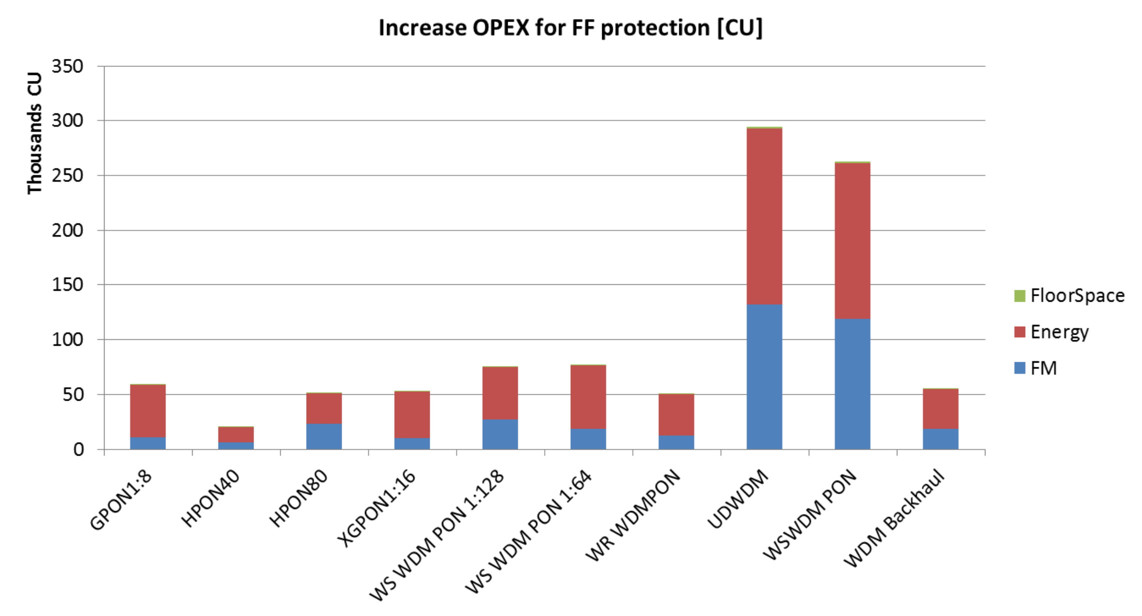


Figure 56 Increase of OPEX when offering FF protection in rural areas

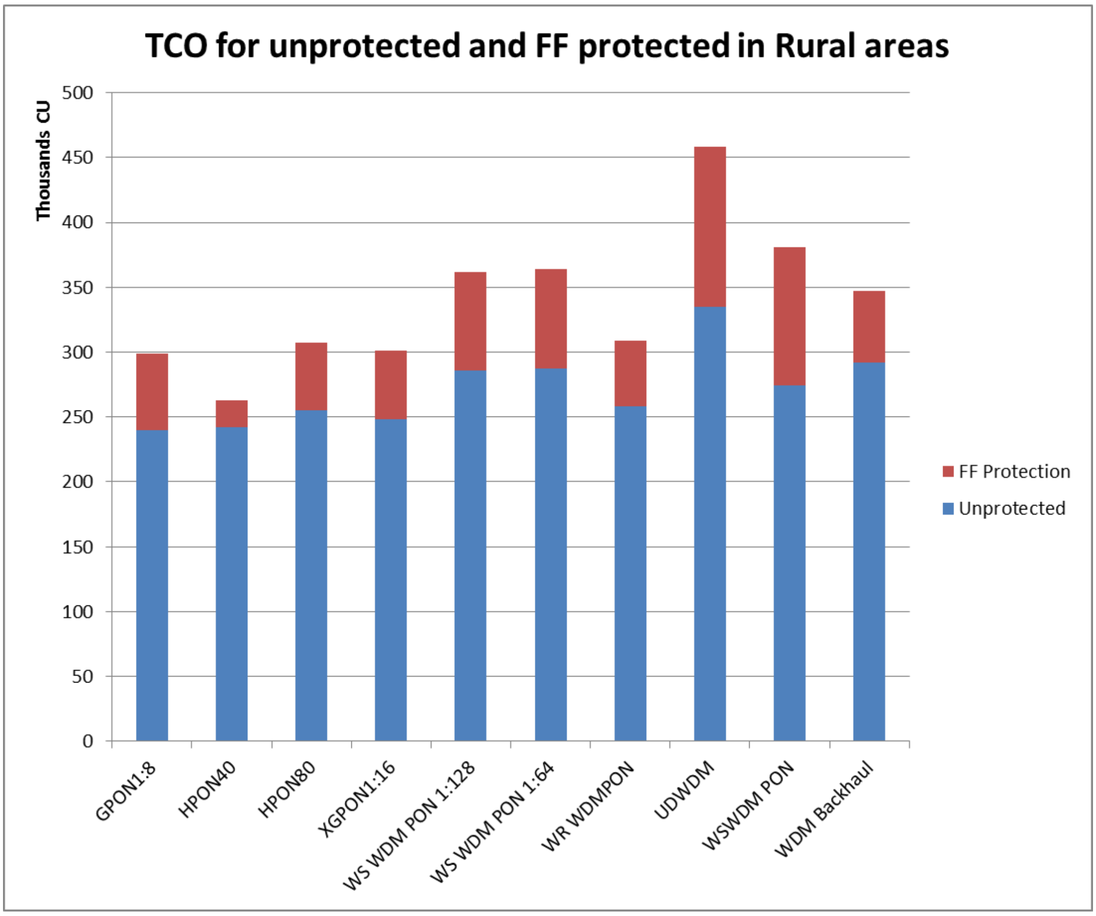


Figure 57 TCO for unprotected and FF protected solutions in rural areas

5. NGOA Cost Assessment: Migration: NP Greenfield

This section evaluates the cost of the NP Greenfield scenario, which considers the cost evaluation from non-optical access networks (e.g. copper network) to the NGOA network.
This cost assessment has been done for the aggressive node consolidation for the three types of area: DU, U and R. In this study, the PIP infrastructure assumes some existing and available infrastructure, the "S" scenario as presented in Section 3.1.4.

5.1. Dense Urban areas

Figure 58 compares the total CAPEX distribution from 2020 to 2030. It can be observed, that the in-house infrastructure is the same for all the architectures. The CPE equipment cost differs among the architectures, and in the same way as in the brownfield scenario, since the same penetration curve has been considered. However, an important increase of the PIP infrastructure can be observed when compared with the brownfield scenario (Figure 39): for all the architectures, an increase of more than 0.3 million CU can be identified.

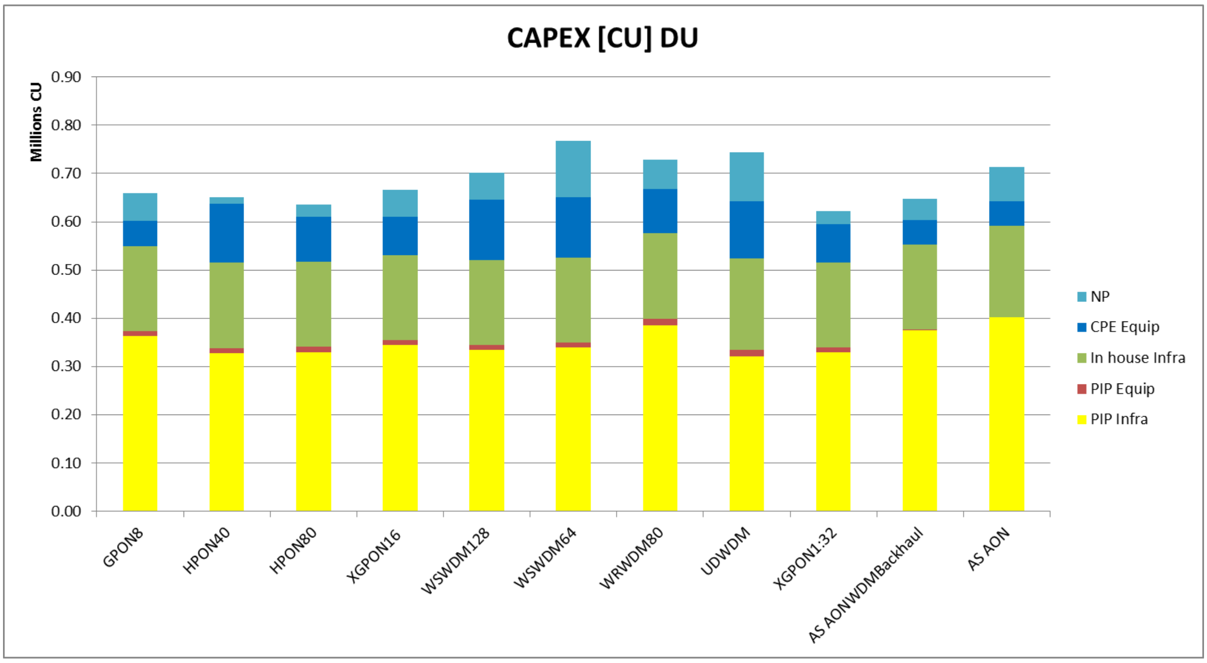


Figure 58 NP Greenfield: Total CAPEX for DU areas

When looking into operational expenditures, as shown in Figure 59, the most important difference with respect the brownfield scenario, is the increase of service provisioning costs due to the higher effort required to connect all users (in brownfield scenario (Figure 40), some savings in service provisioning were obtained because of the connection of users to previous solutions such as GPON, which in the greenfield cannot be reduced).

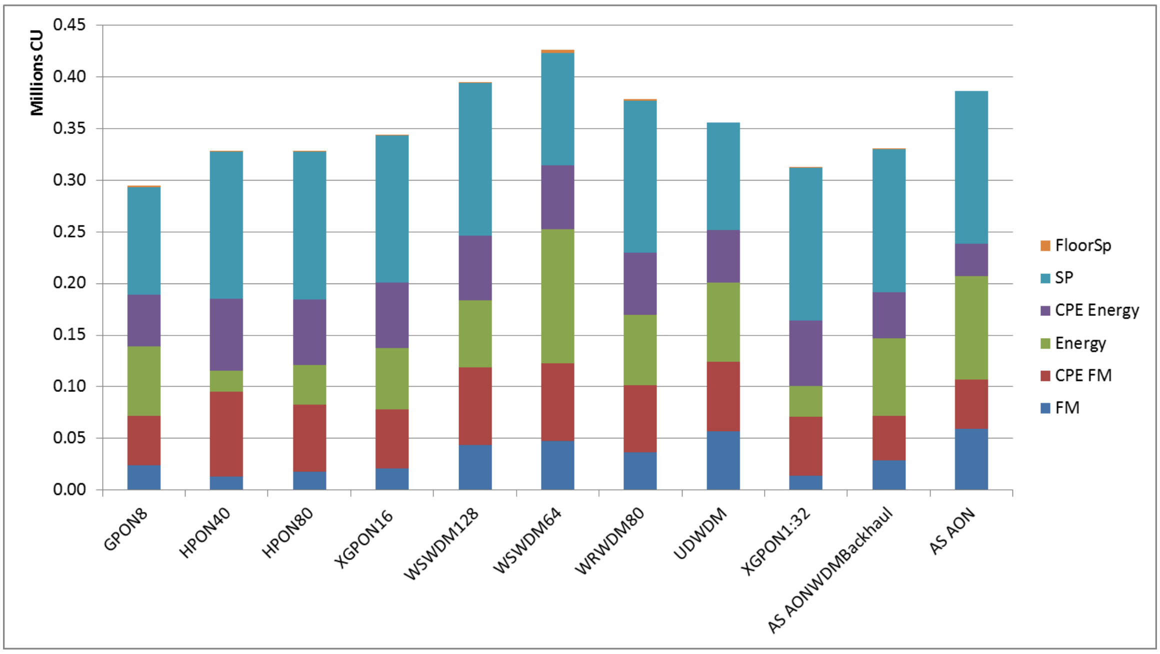


Figure 59 NP Greenfield: Total OPEX for DU areas

5.2. Rural areas

The total CAPEX and OPEX comparison in rural areas have been presented in Figure 60 and Figure 61 respectively. The most important differences with respect dense urban areas in the significant increase of PIP Infrastructure, since the distance to users is much longer.

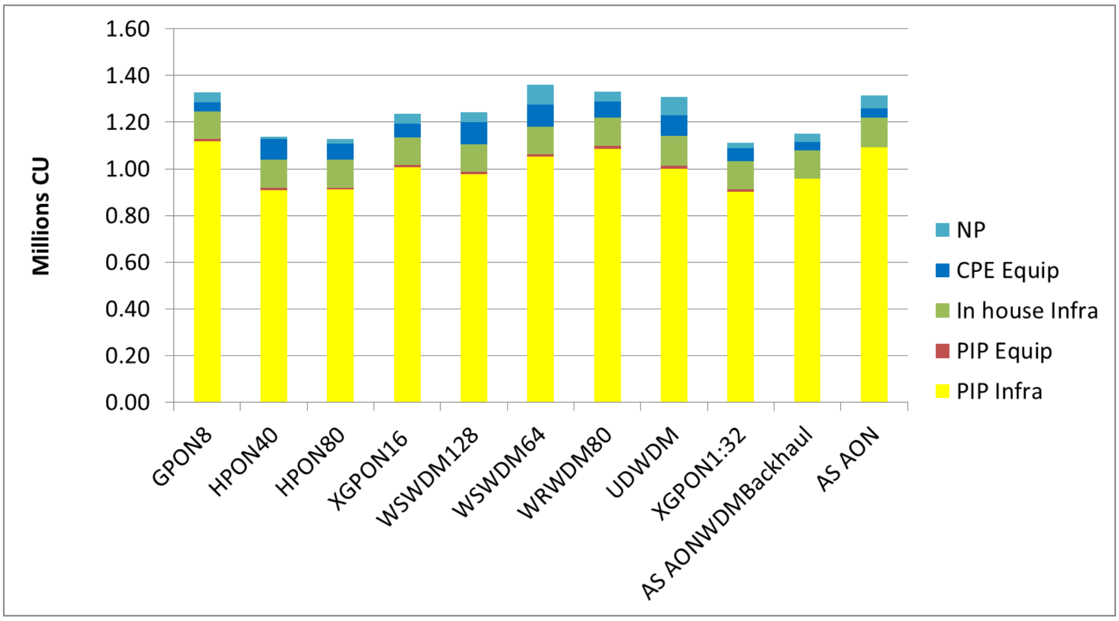


Figure 60 NP Greenfield: Total CAPEX for rural areas

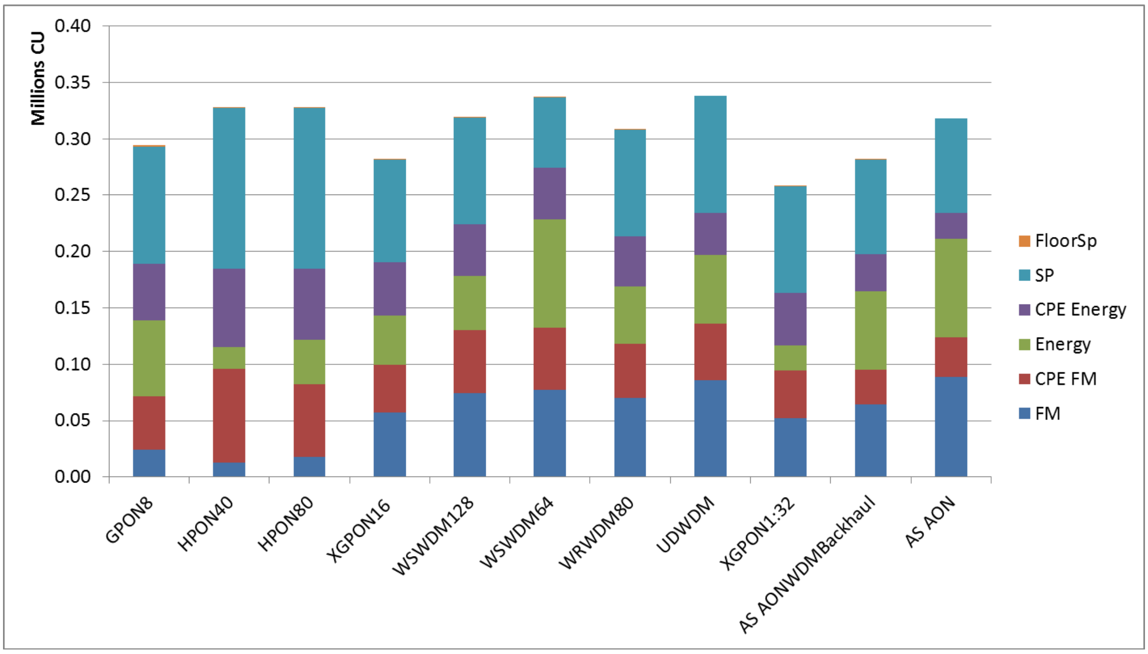


Figure 61 NP Greenfield: Total OPEX for rural areas

6. NGOA Cost Assessment: Migration: Pure Greenfield

The results of the analysis are presented for two different consolidation scenarios, the basic scenario with non-node consolidation and the aggressive consolidation scenario; and for four different architectures. The corresponding results are shown in Figure 62 and Figure 63 respectively.

The lower the part of available infrastructure, the higher the costs are, an obvious and assumed result. In rural areas, the relative delta is significant smaller than in dense urban or urban areas.
In the non-node consolidation scenario, one can see that the infrastructure cost for the scenarios HPON40, HPON 80 and GPON 1:8 are more or less similar in all different area types. This reflects very well that this three technologies use basically the same infrastructure and the sharing with the help of optical power splitters in the first mile. In contrast the AON case requires significant more fibres and therefore infrastructure and resulting digging. This adds some 10-20% for the brownfield “XL” scenario, 5-15% for the brownfield “S” scenario and about 3-7% for the Greenfield scenario in comparison to the other technologies. This relative decrease is caused on one hand side by the increasing basis of investment and on the other by some optimisation in the selected deployment scenario for AON.
The results for the aggressive node consolidation scenario can be found in Figure 63. It includes the cost for the aggregated area (which is a factor per area type of the results in 3.1.2) and the costs for the backhaul from the traditional (non-node consolidated) to the consolidated location. The AON P2P scenario is migrated to WR-WDM PON for the node consolidation purpose (as Figure 13 in Section 3) by replacing active equipment with passive AWGs at legacy local exchange office and extends all active equipment to the node consolidated location. This migration path can minimize the migration effort by avoiding any changes in the first mile fibre infrastructure (from PCP0 to PCP5). On the other hand, because the first mile fibre infrastructure is same as AON P2P the WR WDM is at a higher level of costs for the infrastructure.

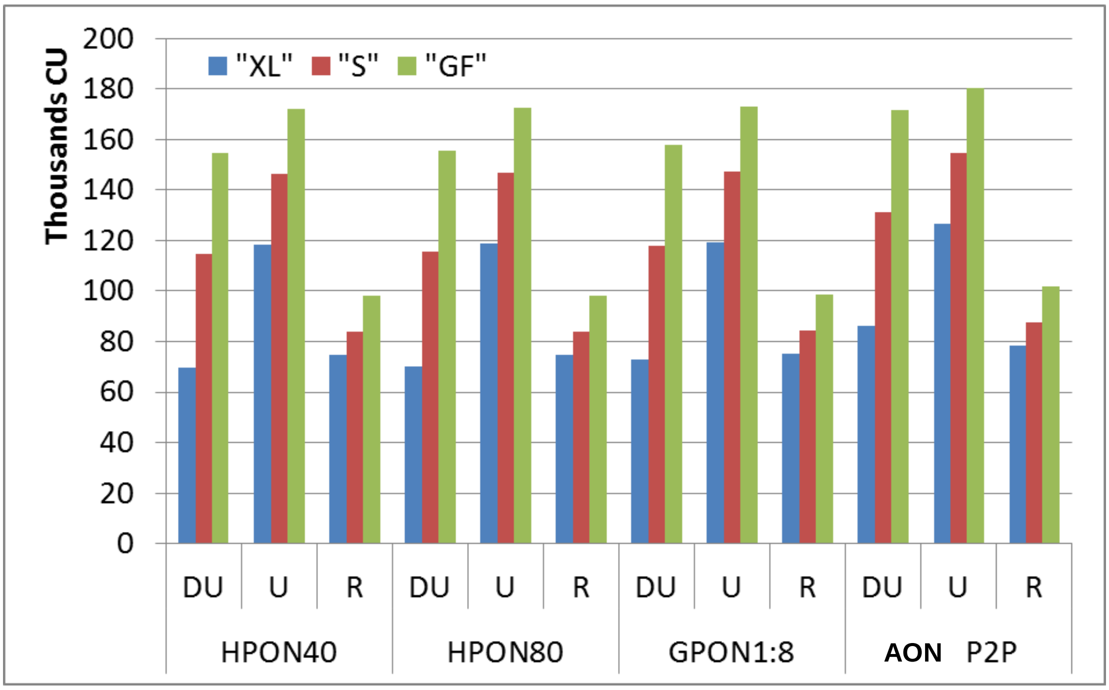


Figure 62 Non-node consolidation: Infrastructure cost of different architectures taking into account different duct availability assumptions: Greenfield "GF", partial "S" and extended "XL"

Still, the delta between HPON40 and HPON80 is not significant, the approaches are relatively similar. In contrast the GPON 1:8 has much higher costs (8-15%) compared to HPON40/80 and is at a similar level than the WR WDM architecture.

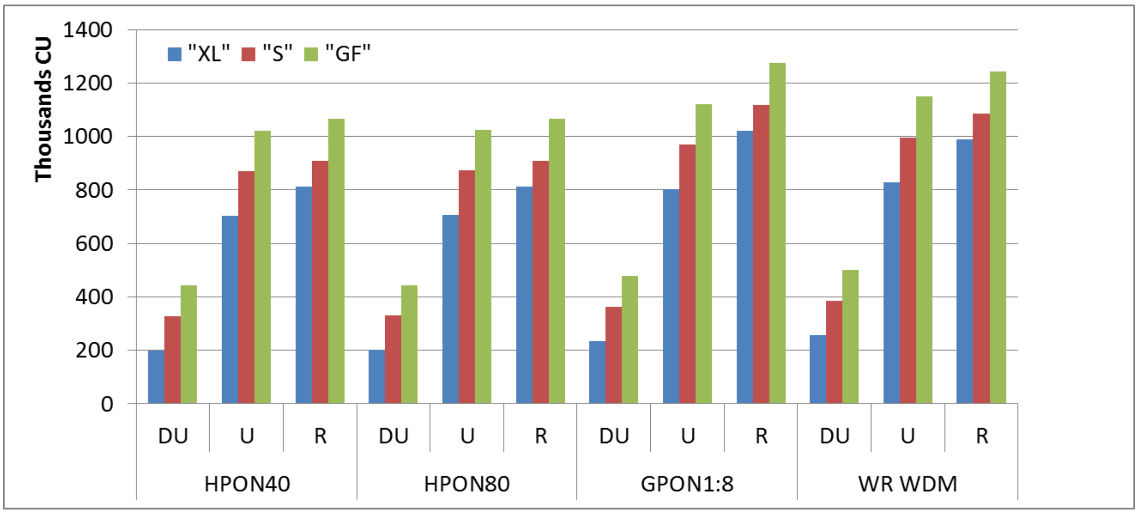


Figure 63 Aggressive node consolidation: Infrastructure costs of different architectures for different duct availability degrees: "GF", "S" and "XL" (refer to Section 3.1.4).

7. Further studies on "Migration: NP Brownfield" cost assessment

7.1. Identification of cost key parameters

Let us now identify which are the cost key parameters of the different solutions considering the NP Brownfield case study and considering the undiscounted TCO from 2020-2030. For that purpose, the different cost categories are evaluated as percentage of the total cost. This study has been summarized in Table 4 for the aggressive node consolidation and in Table 5 for the non-node consolidation. The parameters with higher percentage are highlighted in darker blue. The last column shows the total cost.

Looking at the most coloured columns, SP and CPE equipment are important cost factors for all the architectures. To be noticed that the huge investment of PIP infrastructure at 2010 is not included in this brownfield study. However, some architectures have other important factors:

- The SP factor is dominant for AON P2P in Table 5 and AON WDM backhaul in Table 4 because manual connection is required for the SP event of adding or cancelling subscribers.
- Node consolidation requires high PIP infrastructure for all architectures except HPON40 which can reuse the same as the previous traditional GPON1:32. Significant investment is required to upgrade GPON (from 1:32 to 1:8) not only to replace splitters but also to interconnect them to the PCP5 and PCP6.

A general conclusion is that all parameters which scale with the number of users (i.e. CPE parameters, In building infrastructure) have an important impact on the total cost. In particular, the cost and the energy of CPEs, should be kept low so that the total cost decreases. The CPE failure rate has also an impact to the cost, but is mainly due to the fact that the higher the failure rate is, the more failures there are, and the more CPE have to be replaced (and hence, the CPE cost has also an impact to the CPE fault management cost).

Table 4 Key cost factors (as % of the TCO) in the aggressive node consolidation scenario

		PIP Infra	PIP Eq.	In Building Infra	CPE Eq	NP	FM	FM CPE	Energy	Energy CPE	SP	Floor space	Total [CU]
DU	GPON8	7.3	2.22	9.86	9.86	9.9	5.06	9.72	13.87	10.45	21.43	0.27	484213
	HPON40	0.13	0.1	9.98	25.48	2.95	2.52	17.28	4.11	14.55	22.8	0.09	478307
	WSWDM128	1.12	0.1	8.1	21.11	9.56	7.43	12.64	10.96	10.46	18.39	0.13	592823
	WRWDM	1.80	2.62	8.69	16.78	11.04	4.03	11.78	12.44	10.82	19.84	0.17	564366.00
	AON WDM Backhaul	0.13	0.18	9.82	9.58	9.84	7.69	8.72	16.32	9.11	28.55	0.07	485976.00
	UD WDM	0.39	0.31	7.53	18.92	15.78	8.96	10.67	12.11	7.96	17.21	0.14	633518
U	GPON8	16.79	1.96	8.69	8.69	8.74	8.42	8.57	12.22	9.21	16.56	0.15	629633
	HPON40	0.92	0.09	9.72	24.79	2.87	7.01	16.82	4	14.15	19.55	0.07	563471
	WSWDM128	7.14	0.09	7.46	19.51	8.84	10.37	11.7	10.13	9.66	15	0.1	734985
	WRWDM	11.34	2.25	7.53	14.54	9.57	9.28	10.21	10.79	9.38	15.00	0.11	726771
	AON WDM Backhaul	0.89	0.18	9.36	9.12	10.48	11.75	8.31	16.36	8.67	24.84	0.05	585165
	UD WDM	2.74	0.30	7.16	18.07	15.33	12.28	10.20	11.77	7.61	14.55	0.00	757513
R	GPON8	37.83	1.4	6.21	6.21	6.24	10.45	6.12	8.73	6.58	10.15	0.08	570300
	HPON40	1.97	0.09	9.22	23.52	2.73	13.16	15.96	3.8	13.43	16.06	0.05	384196
	WSWDM128	14.24	0.08	6.65	17.42	7.9	13.95	10.44	9.05	8.63	11.58	0.06	532724
	WRWDM	22.64	1.99	5.66	10.93	7.21	11.25	7.68	8.11	7.05	17.43	0.04	625464
	AON WDM Backhaul	1.86	0.16	8.68	8.46	9.32	17.51	7.71	17.68	8.04	20.54	0.04	408244
	UD WDM	5.71	0.29	6.61	16.68	14.98	16.19	9.41	11.50	7.02	11.62	0.00	531165

Table 5 Key cost factors in the non-node consolidation scenario

		PIP Infra	PIP Eq.	In Building Infra	CPE Eq	NP	FM	FM CPE	Energy	Energy CPE	SP	Floor space	Total [CU]
DU	GPON8	2.32	2.74	12.14	12.14	7.03	4.30	11.96	7.79	12.86	26.40	0.33	137950
	HPON40	0.00	0.09	9.98	25.47	3.10	2.52	17.28	4.11	14.54	22.79	0.12	167756
	WSWDM128	0.00	0.10	8.14	21.33	9.76	7.50	12.78	11.07	10.57	18.58	0.16	205695
	AON P2P	0.00	0.00	11.30	11.02	12.42	5.46	10.04	9.85	10.48	28.84	0.61	148203.368
	UD WDM	0.00	0.31	7.57	19.02	15.86	9.01	10.73	12.18	8.01	17.30	0.00	220896.08
U	GPON8	1.28	2.71	12.01	12.01	6.95	9.72	11.83	7.70	12.72	22.87	0.21	77251
	HPON40	0.00	0.09	9.79	24.97	3.04	7.06	16.94	4.03	14.26	19.69	0.13	94779
	WSWDM128	0.00	0.10	8.01	21.00	9.60	11.14	12.58	10.90	10.40	16.12	0.15	115774
	AON P2P	0.00	0.00	11.06	10.78	12.15	10.44	9.82	9.64	10.25	25.38	0.46	83868.848
	UD WDM	0.00	0.31	7.36	18.58	15.76	12.63	10.48	12.10	7.82	14.96	0.00	124812.44
R	GPON8	1.86	2.55	11.32	11.32	6.56	17.26	11.17	7.27	12.01	18.52	0.16	28993
	HPON40	0.00	0.09	9.37	23.92	2.91	13.39	16.24	3.86	13.67	16.34	0.22	35031
	WSWDM128	0.00	0.10	7.73	20.27	9.28	16.23	12.15	10.52	10.04	13.50	0.20	42450
	AON P2P	0.00	0.00	10.52	10.26	11.56	17.84	9.35	9.18	9.76	21.20	0.33	31210
	UD WDM	0.00	0.31	7.01	17.69	15.89	17.17	9.98	12.19	7.44	12.32	0.00	46440.39

7.2. Cost evaluation of the equipment purely used for migration

This section presents the cost evaluation of the equipment that is only required during the migration period, which allows the co-existence of two parallel access deployment (the traditional and the NGOA network). This specific migration equipment is only required for some migration scenarios such as GPON to HPON or WS WDM PON.

Table 6 Migration dedicated equipment cost [CU]

		Aggressive node consolidation	Non-node consolidation
HPON40& WS WDM PON 1:128	DU	897.6	314.4
	U	1027.2	175.2
	R	664.8	62.4
HPON80	DU	1795.2	628.8
	U	2054.4	350.4
	R	1329.6	124.8

As it is shown in Table 6, the costs of the equipment required just for migration purposes, varies depending on the area and the node consolidation. However, all these costs turn to be 1% or less of the PIP needed by NGOA, and hence, it can be considered negligible.

7.3. Impact of migration time duration on the cost assessment

This section analyses the impact that the migration duration has on the cost. Hence, as first study, the cost of the migration from GPON1:32 to HPON40 in the non-consolidation for dense urban areas is evaluated for a 1-year and 3-year migration times. For the 1-year migration, GPON1:32 runs from 2010 to 2019, and HPON40 runs from 2020 to 2030. However, for the 3 year migration study, there is a coexistence of GPON and HPON from 2020 to 2022. The cost evolution of both cases is shown in Figure 64. It can be observed that the CPE Equipment peak in the 1-year migration relaxes in the 3-year migration because the purchase of CPE for the migrated users is spread during the migration time. The same occurs with the service provisioning costs, the migration effort is spread over 3 years instead of being concentrated in the migration year. The NP equipment is assumed to be the same in both cases, since the worst case assumption of user distribution to be migrated is assumed. In case the migration of users is done per area, the NP cost could be more gradual during the 3-year migration.

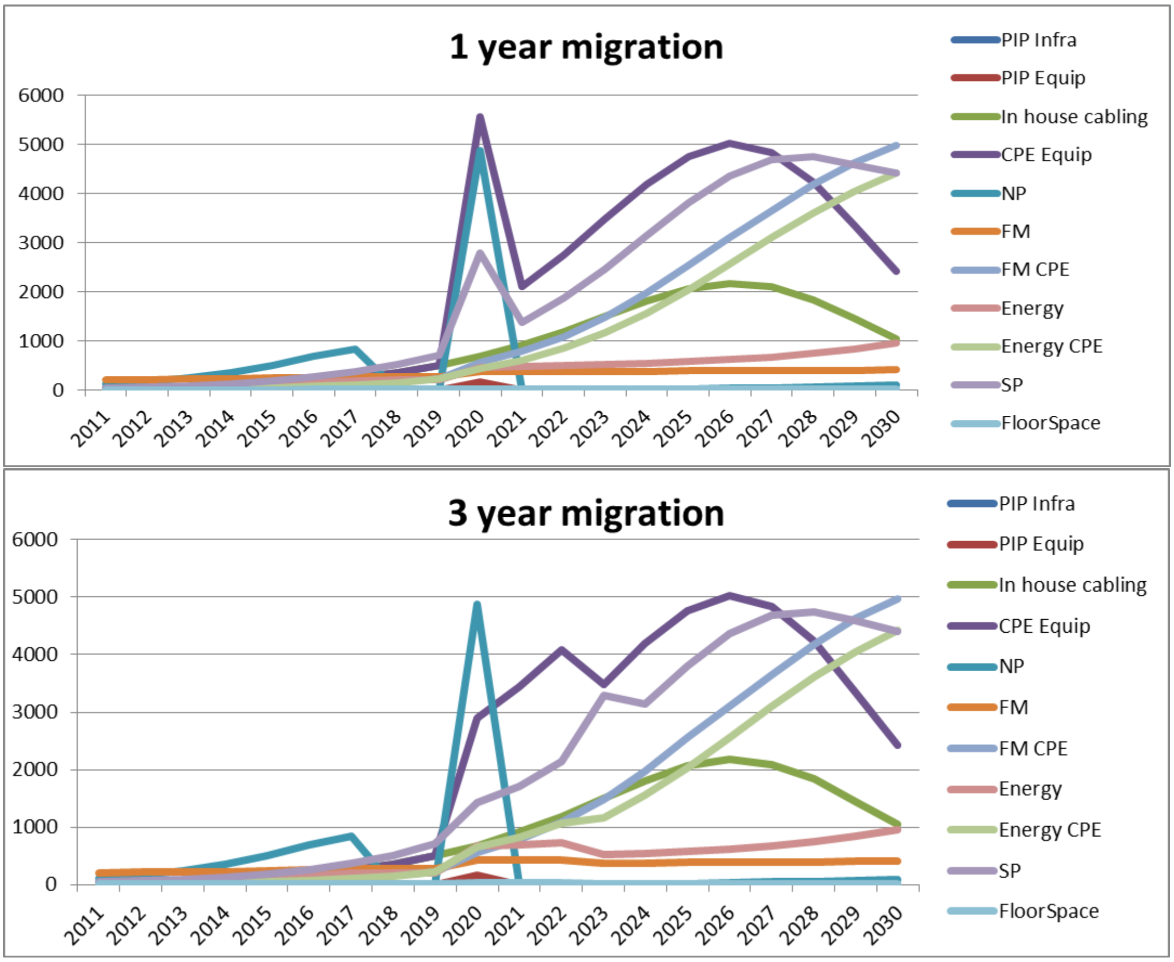


Figure 64 Cost evolution for 1 (top) and 3 (bottom) year migration duration

When looking into the sum of all costs from 2020 to 2030, as shown in Table 7, the same conclusions can be observed, that is, a longer migration increases the SP but also the FM and energy since the GPON should be maintained longer time.

Table 7 Sum of costs 2020-2030 when the duration of the migration is one and three years

	1 year	3 years
PIP Infra	0	0
PIP Equip	157	157
In house cabling	16744	16744
CPE Equip	42724	42723
NP	5211	5211
FM	4224	4403
FM CPE	28983	28983
Energy	6899	7557
Energy CPE	24398	25051
SP	38223	38319
FloorSpace	205	237
TOTAL	167769	169386.001

7.4. Impact of migration starting time on the cost assessment

This section analyses the impact that the migration year has on the cost. Hence, as first study, the cost of the migration from GPON1:32 to HPON40 in the non-consolidation for dense urban areas is evaluated considering as starting migration 2020 or 2023. The main difference is the number of users that are connected to the GPON at the year of the migration (more than 3,600 users should be migrated when migration starts in 2020, whereas more than 10,000 users should be migrated when migration starts in 2023).
The cost evolution of the migration in 2020 and 2023 of GPON1:32 to HPON40 in a Dense urban area with non-node consolidation is shown in Figure 65. It can be observed that the peak cost is moved to the migration year. However, the peak cost is significantly higher when the migration starts in 2023 since the number of users that has to be migrated and therefore, need new CPE, is higher than in 2020. Also, the effort of service provisioning is significantly higher when the migration is postponed.
However, when looking at the sum of all costs from 2020 to 2030, as shown in Table 8 , it can be observed that the increase of SP and CPE costs is compensated somehow by the savings in terms of energy, FM and floor space, since GPON consumes and fails less than HPON.

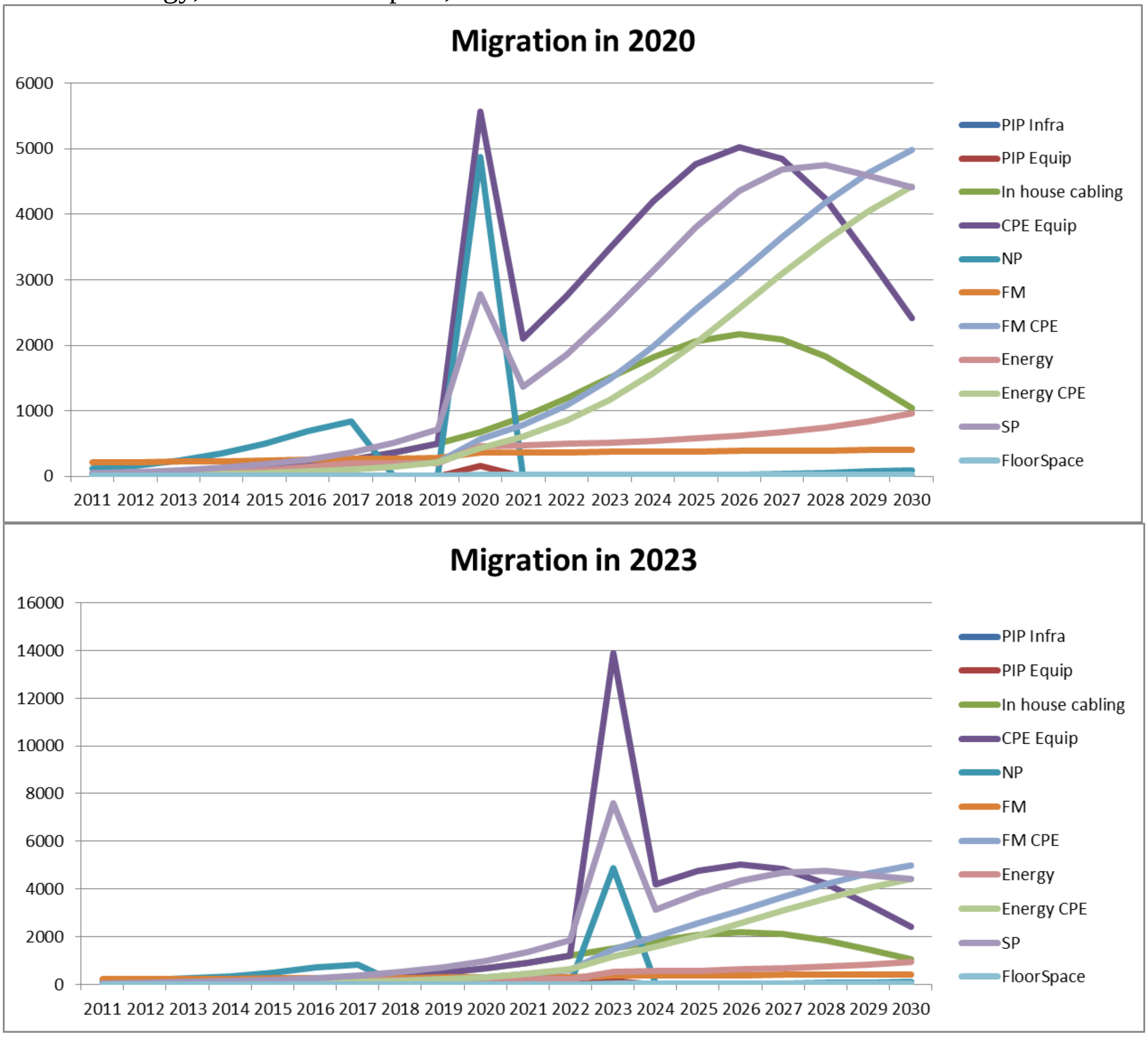


Figure 65 Cost evolution for migration starting in 2020 (top) or 2023 (bottom)

Table 8 Sum of costs 2020-2030 when starting the migration in 2020 and in 2023

	2020	2023
PIP Infra	0	0
PIP Equip	157	157
In house cabling	16744	16744
CPE Equip	42724	45498
NP	5211	5212
FM	4224	3976
FM CPE	28983	27904
Energy	6899	6124
Energy CPE	24398	23883
SP	38223	41552
FloorSpace	205	181
TOTAL	167768.9	171231.3

8. Sensitivity analysis

In this deliverable different estimations and predictions have been shown for the total cost of ownership of an NGOA network. These figures are the results from using the TCO tool developed within WP5 taking into account the requirements as described in WP2, the architectures as described in WP3 and the components in WP4. Results from the calculations in this tool will flow to WP6 for further analysis. Clearly the reliability of the TCO tool should be investigated and in extension the effect of potential changes in the input parameters on the outcome total cost of ownership is very important.

In order to test the tool and get a better feeling of its input parameters and the effect on the outcome a set of sensitivity analysis studies have been performed. In discussion with the other work packages – in their interest and from their background – the following studies have been defined:

1. Impact of the requirements from WP2 on the outcome of the total cost of ownership. The main requirements of OASE have been to provide a sustainable bandwidth of 500 Mbps or higher over a distance of 100km and with a fanout of 1000 customers per feeder fibre. Clearly loosening one of these requirements will have an impact on the other. In this study we increased the fanout in order to check the gains by better multiplexing and equipment with a higher aggregation factor.
2. Impact of regional differences from WP6 on the outcome of the total cost of ownership. The TCO tool has been constructed with predefined values for several parameters inherently giving it a country bias. Different sets for these parameters – e.g. loans, floor space, energy, etc. – have been constructed in cooperation with WP6 and have been calculated for the different architectures in one sensitivity study.
3. Impact of the relation of the CPE price and the OLT price. When looking at the impact of the installation of an NGOA, typically both the CPE and the OLT will take the largest part of the costs. This is even more the case when analyzing the business case and taking discounting into account, as investment costs are coming early in the project and will weigh more on the discounted outcome. In this study the impact of changes in the CPE price on the TCO outcome for the HPON 40 and the HPON 80 architecture will be analyzed.
4. Impact of the adoption rate on the total cost of ownership and especially on the non-discounted and discounted cost per customer subscription year have been taken into account.

All studies as described in this list have been conducted and the input and outcome results are discussed in more detail in the following subsections.

8.1. Impact of loosening the OASE requirements

The setup and initial phase of the OASE project has put forward the main hard requirements expected for a next generation optical access network. The main parameters in these have always been the bandwidth offered to the customer (500Gbps sustainable) the fanout of the solution (1000 customers on a feeder fibre) and the reach of the optical signal from OLT to the customer (up to 100km). Clearly these requirements are interconnected as a higher fanout will reduce the bandwidth and reach. Clearly a lower bandwidth requirement and/or reach requirement could as such prove beneficial for the cost per customer and as such in total. This section will look into the impact of the fanout on the different architectures under consideration in OASE WP5 cost studies. It should be noted that not all architectures have been designed to work with a much higher fanout or have no suitable equipment to reach such high fanout. Additionally the TCO calculation did not consider a realistic modeling for each architecture when considering a fanout not initially taken into account and in those cases additional variations could not be taken into account.

Scenario analysis on top of the TCO calculation within WP5 allows us to have a clear view on the effect of increasing the fanout. We have increased the split ratio defined in the TCO for each solution and we have fixed the following assumptions for the case to calculate:

Penetration Curve for PIP	**Everything in 2010**
Penetration Curve for NP	**WP6 likely**
Area_Type	**Rural/Urban/Dense Urban**
Consolidation_Type	**7500**
Traffic Scenario	Med
Simplex / duplex fiber cable solution	1
Maintenance duration per occupied slot in [h]	0.44
Maintenance costs for material per occupied slot in [h]	22
Costs for maintenance contracts in [€]	700,000
Costs for software licences in [€]	250,000
Conversion factor	50
Cost for kW per year for indoor	54
Cost for kW per year for outdoor	64
Cost for kW per year for ONT	39
Inflation	3%
Migration year	2020
Soft migration years	0

In the case of the GPON and XGPON solutions, we see that the cost is the highest at the lowest split ratio and will decrease with an increasing split ratio to 2/3 of the original value. The XGPON will always have a higher cost than the GPON solution. Still the XGPON will offer the customers a higher bandwidth and as such can have a higher fanout within the same bandwidth requirements.

In the case of the HPON we see that the solution with 40 channels is most cost efficient for lower fanout and the 80 wavelength solution will prove less costly somewhere around a fanout of 1000 and will reach significantly lower costs from there on. The figure below gives a view on the costs of all solutions and clearly shows how much lower costs can be reached with all but some solutions, when using a higher fanout. It will be the operator's choice to tune the bandwidth and reach requirements to this gain in costs by stretching the fanout.

We have found that the differences between the different architectures do not depend on the area type (dense urban, urban or rural) nor on the duct availability which were parameters taken into account in this sensitivity analysis. In Figure 66 we show the cost of each architecture in a 7500 node consolidation scenario to its total fanout, averaged over all sensitivity scenarios run for this combination (e.g. for all area types and duct availabilities). As mentioned we found the same figure for dense urban or urban or rural separately, except for the cost values in the left axis.

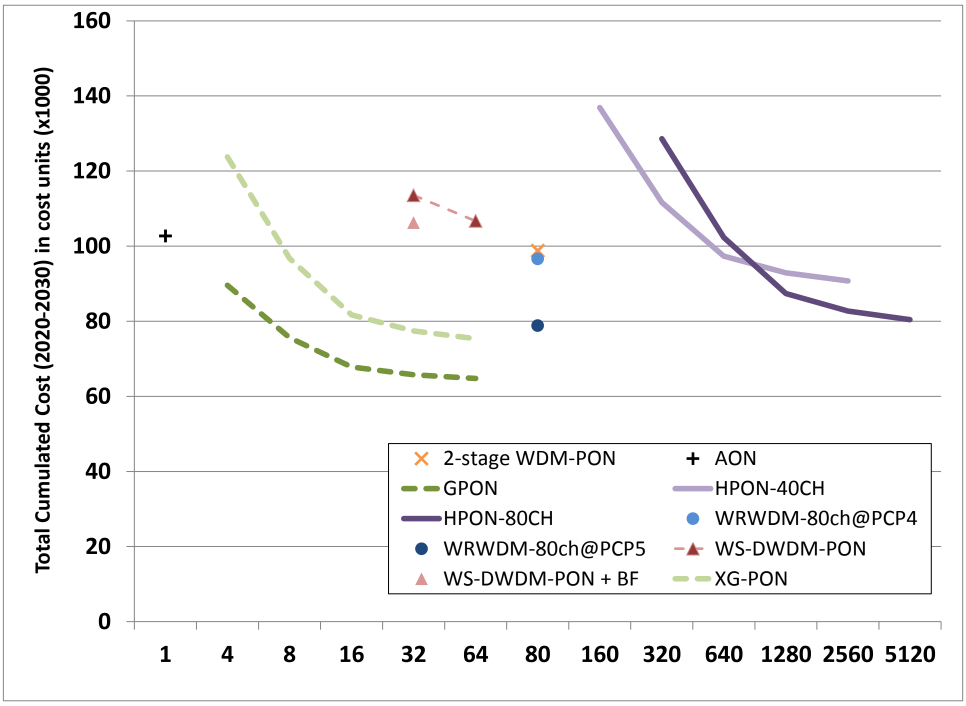


Figure 66: Cumulative non discounted cost as a function of the fanout, averaged over all variations in a 7500 node consolidation scenario

Figure 67 gives the same overview for the case of a 1000 nodes consolidation. Clearly this has again the effect that the area considered is larger. We also see in this how:

- HPON 80 becomes the most cost efficient solution already at a fanout of 640, which is at lower fanout than in case of the non-node consolidation.
- XGPON comes closer to GPON in the higher fanout scenarios
- AON moves a little down in the cost comparisons
- The differences in WS-DWDM-PON are higher and decrease with increasing fanout, and the solution with a bandfilter becomes the cheapest WS-DWDM solution.

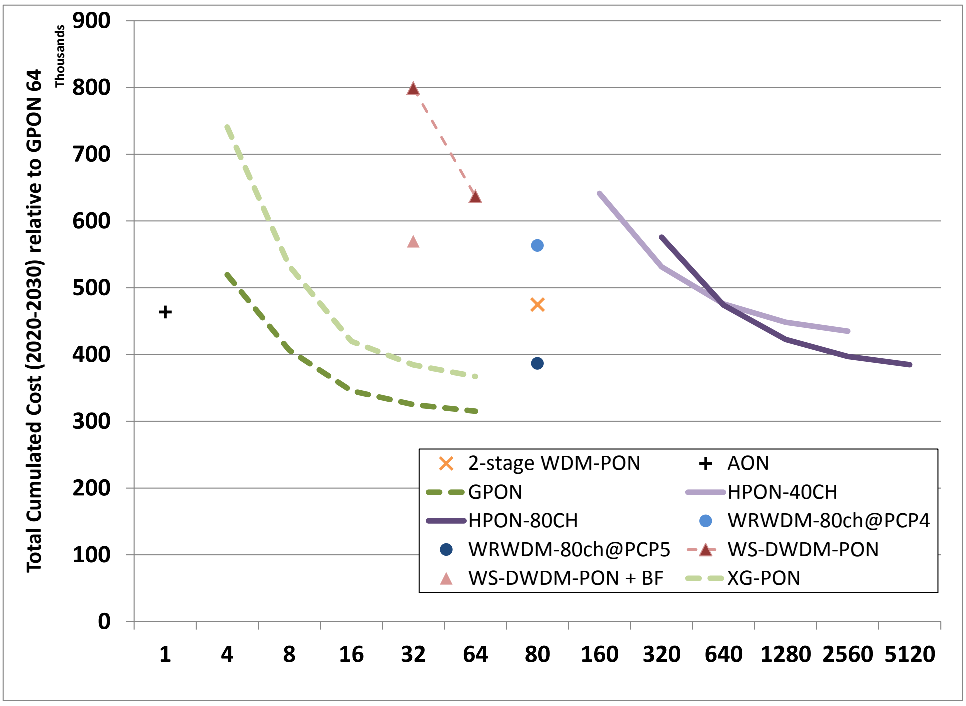


Figure 67: Cumulative non discounted cost as a function of the fanout, averaged over all variations in a 1000 node consolidation scenario

In relation to the cheapest cost in the analysis (see Figure 68), the asymptotical cost of the GPON solution (GPON64) the costs of lower fanout quickly rises to twice the cost of a much higher fanout. Clearly the higher fanout solutions will profit from this and the operator will have to balance fanout and cost savings to its possibilities to provide high bandwidth and increase this bandwidth in the future.

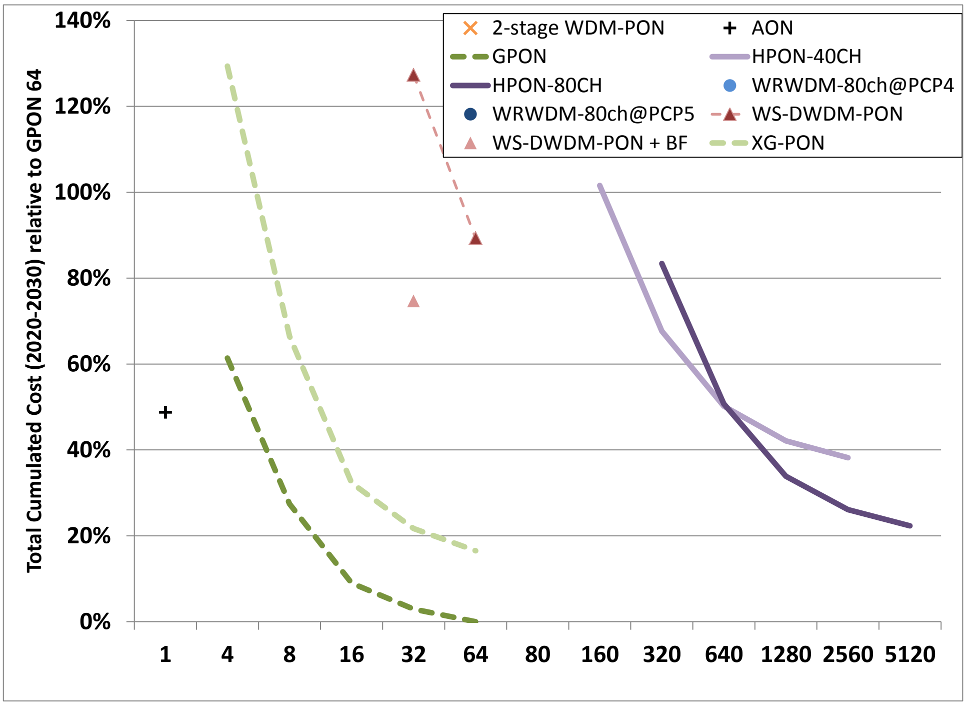


Figure 68 Increase in average costs of different architectures in function of fanout and relative to the average cost of GPON 64 (asymptotical minimum)

8.2. Regional Differences

To check the impact of the regional differences a study has been performed to get an idea of the main variations in input parameters between the different countries. Table 9 shows the considered set of input parameters for which important variations are expected and for each of these parameters the situation in the regions Belgium, the Netherlands, Germany, Sweden Greece and Hungary have been added. These regions were selected in cooperation with WP6, as they have been considered as base cases for the business model construction in WP6 or have relations to the partners within the project. Additionally the extreme values which we found for Europe have also been selected and are represented as lowest and highest in Table 9. We have been unable to find the input to some of the data we initially set out to use in these studies. These have been indicated in red in the table.

Table 9: Set of parameters influenced by the regional differences, applied to the set of considered regions and their extremes

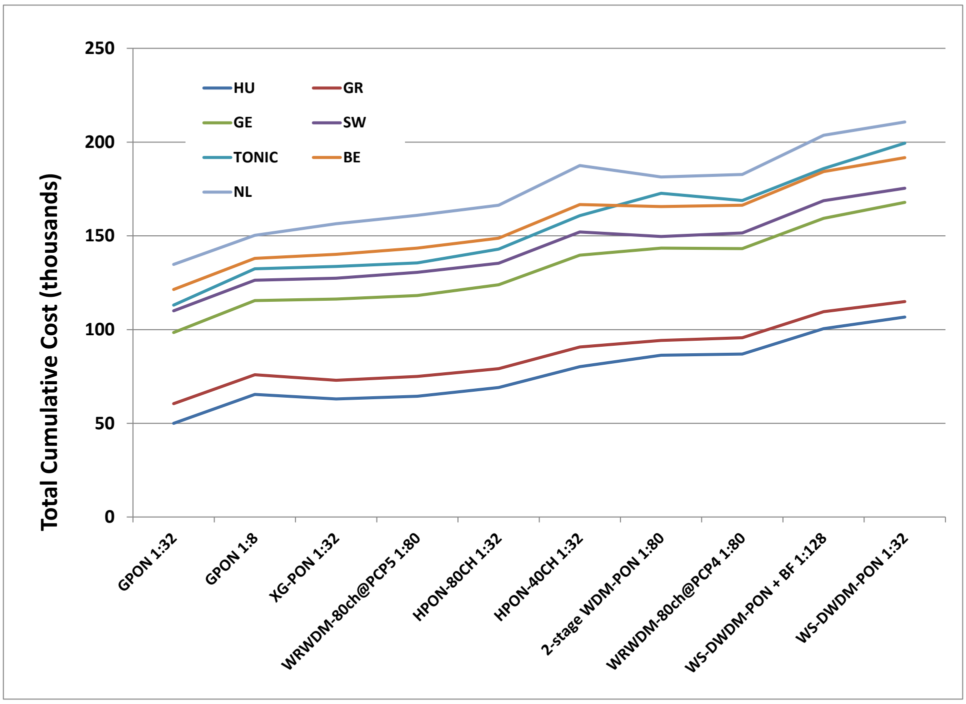
	Belgium	The Netherlands	Germany	Sweden	Greece	Hungary	lowest	highest
energy cost residential customers (€/kWh)	0.21	0.22	0.25	0.21	0.13	0.17	0.08	0.30
energy cost industrial customers (€/kWh)	0.09	0.08	0.10	0.07	0.08	0.09	0.05	0.16
floor space (€/m2*y)	186.97	330.30	193.03	356.36	185.30	166.67	82.88	990.90
labour costs (€/h)	28.96	25.30	21.70	27.10	13.10	5.52	5.52	29.00
BB penetration subscriptions per capita (%)	30.80	38.50	32.00	31.70	19.90	20.60	14.00	38.50
average household size (people/HH)	2.30	2.20	2.00	2.10	2.70	2.60	2.80	2.20
estimation of BB penetration per HH (%)	70.84	84.70	64.00	66.57	53.73	53.56	39.20	84.70
regulated price NP to PIP (€/customer)	8.03	12.14	??	??	??	??	??	??
price SP to NP (€/customer)	18	??	??	??	??	??	??	??
adoption	??	??	??	??	??	??	??	??
revenue residential broadband	??	??	??	??	??	??	??	??
maintenance cost	??	??	??	??	??	??	??	??
availability of existing ducts	??	??	??	??	??	??	??	??
digging costs	??	??	??	??	??	??	??	??
Area types	??	??	??	??	??	??	??	??
level of competition	??	??	??	??	??	??	??	??

From this set of regional differences a reduced subset has been made – see Table 10 - that can directly be used to calculate a case within the TONIC tool. This means that all cost figures have been translated into the cost units and in the right format for TONIC to work with. In this we have taken a power usage efficiency (PUE) of 2 into account for both indoor and outdoor industrial energy consumption, meaning that every Watt of calculated power consumption will lead to an actual 2 Watts consumed in total. Both floor space costs and labor costs have been related to the base values found in TONIC. In each case the values are in line with those in TONIC, with TONIC close to the Swedish, Belgian and German values which are typically the values for which we had the most easy access from within the project

Table 10: Reduced set of parameters for the regional differences which can be used directly in TONIC and have been related to the original values in TONIC.

	BE	NL	GE	SW	GR	HU	TONIC	lowest	highest
energy indoor (CU/kWy)	30.54	28.05	35.91	25.95	27.00	31.77	54.00	18.30	56.28
energy outdoor (CU/kWy)	36.20	33.25	42.55	30.75	32.00	37.65	64.00	21.69	66.70
energy ONT (CU/kWy)	37.41	38.71	44.55	36.78	22.18	29.94	38.50	14.43	52.28
labour costs (CU/h)	1.16	1.01	0.87	1.08	0.52	0.22	0.90	0.22	1.16
BB penetration (% inhabitants)	70.84	84.70	64.00	66.57	53.73	53.56	74.02	39.20	84.70
floor space (CU/m2*y)	3.74	6.61	3.86	7.13	3.71	3.33	3.33	1.66	19.82

The calculations have been repeatedly run for a selection of the architectures which are most plausible considering a migration from currently existing networks or considering the current typical split rates and splitter equipment of 1:32. Additionally for GPON a 1:8 split ratio has been taken into account. The worst and best scenarios are coinciding with the lowest and highest scenario as described above. Considering the costs, the highest cumulative cost will be found for the highest adoption and for the set of highest sub costs. As a second result, also the cumulative cost per customer is shown, where worst and best here will be coinciding with respectively the highest costs + lowest uptake and lowest costs + highest uptake.



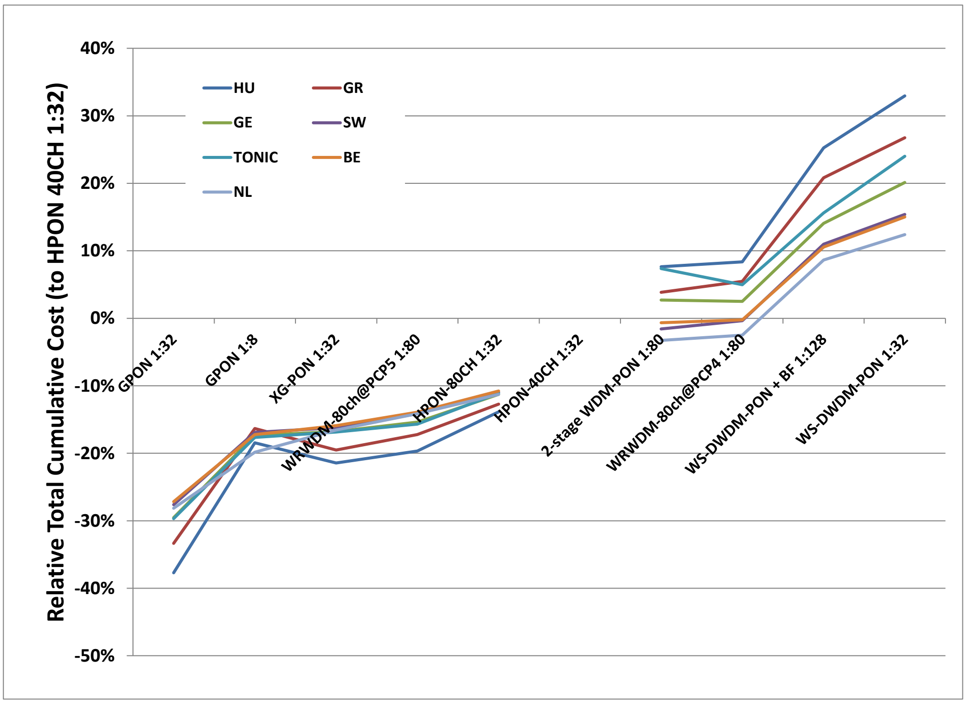
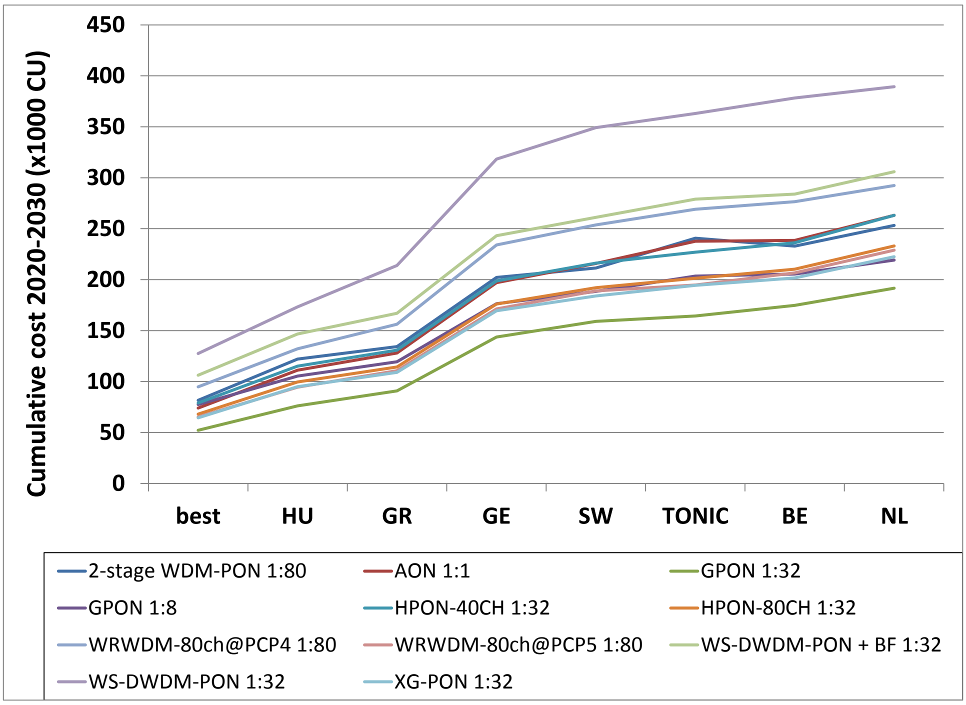


Figure 69: cumulative costs over the period 2020-2030 for the different architectures and regions with relation to the OASE project. (Top) Total cumulative (Bottom) relative to HPON40-1:32

Figure 69 shows the cumulative costs for different architectures over the period 2020-2030 for the different regions. All calculations showed here used as a basis the WP6 likely adoption curve, a 7500 node scenario and a dense urban situation. The top figure gives a view on the costs of each region as a function of the architecture deployed. Clearly the most costly architecture is the WS-DWDM-PON and the most cost efficient architecture might be the GPON 1:32 architecture, but this does not deliver the required bandwidth to be catalogued as an NGOA network. In relation to the total costs of the HPON40ch – 1:32 scenario, as shown in the bottom figure, the most costly architectures will increase costs by 30% while the less costly NGOA architectures could reduce costs with up to 20%. Note that for HPON40 all costs relative to its own will end up in 0% and are as such omitted from this figure.



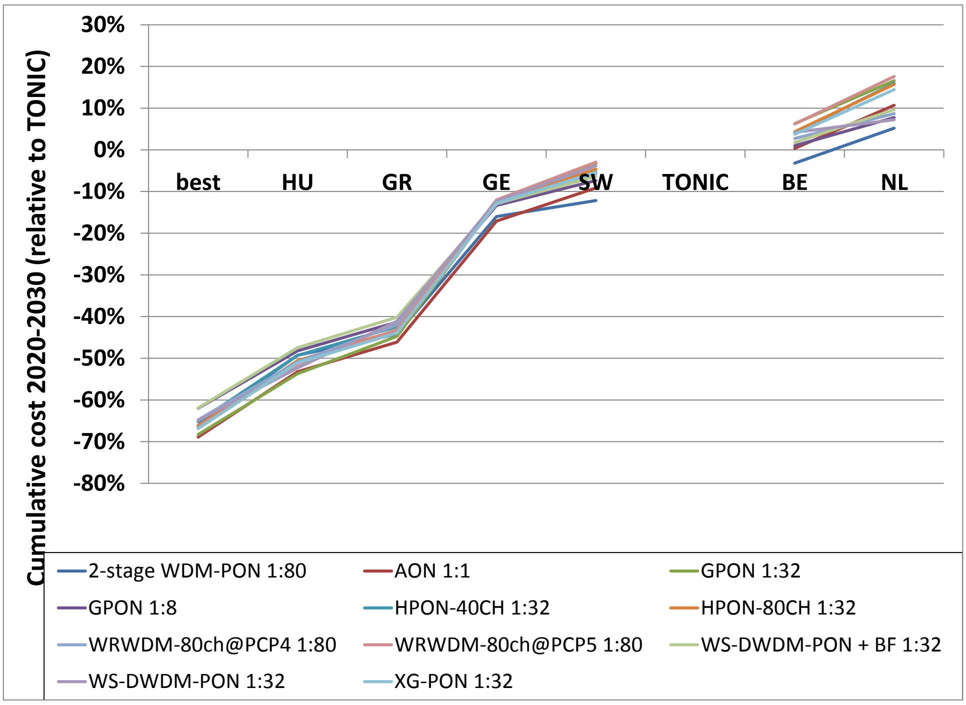
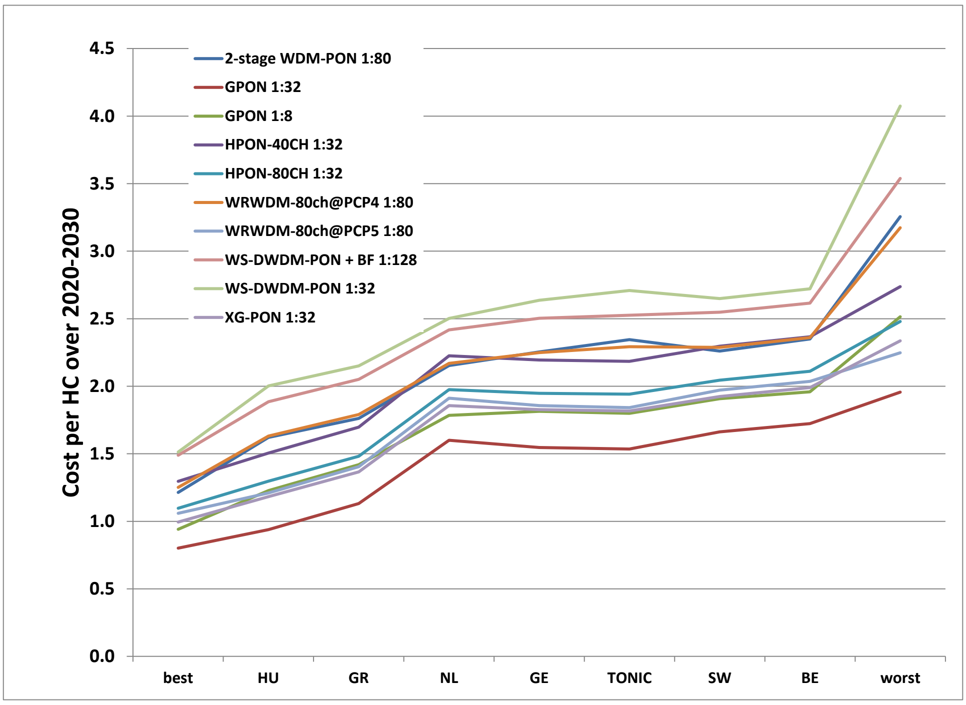


Figure 70: cumulative costs over the period 2020-2030 for the different architectures and regions with relation to the OASE project (Top) Total Cumulative (Bottom) relative to the base case TONIC

Figure 70 shows the cumulative costs for different regions over the period 2020-2030 for the different architectures. Again, all calculations showed here used as a basis the WP6 likely adoption curve, a 7500 node scenario and a dense urban situation. The top figure gives a view on the costs of each region as a function of the architecture deployed. Clearly the most costly region is the Netherlands and the most cost efficient region found is Hungary. The main driver for the total cost is undoubtedly the amount of houses to connect (adoption), making the Netherlands the most expensive scenario. In relation to TONIC region, as shown in the bottom figure, the most costly regions will increase costs by 20% while the least costly

NGOA architectures could reduce costs with up to -50%. Again all 0% in the case of TONIC have been omitted from this figure.

Clearly the regions have a difference in adoption rate and as such an equally interesting view would focus on the cost per end customer subscription. A higher adoption potential will result in both a higher total cost, but also a higher number of customer subscriptions. As such the cost per subscription will be impacted and the increase in cost for the more adoption rich regions will become less expensive and possibly even lower than adoption poor regions.



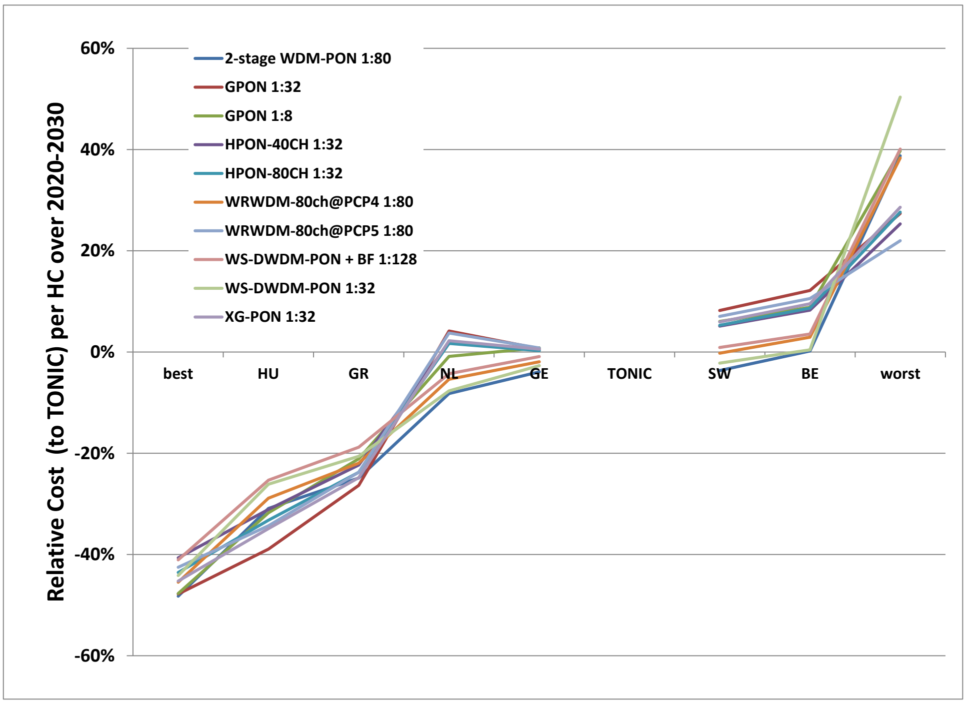


Figure 71: costs per subscription year over the period 2020-2030 for the different architectures and regions with relation to the OASE project.

Figure 71 shows the costs per customer subscription year for the different areas and for the different architectures which have been taken into consideration above. It is important to note in this figure how the adoption could seriously impact the outcome of the business case. The figure indicates very nicely how the Netherlands, although being the highest total cost, does not show the highest cost per customer. It even shows on average the lowest cost per customer of all western European countries and the higher adoption will make up for the higher costs for all sub-parts. We have used the TONIC case as the base case for a relative comparison and the results are shown in the bottom figure. As expected, the German case is closely coinciding with the TONIC case. It also shows how the regions with substantially lower sub costs will have a relatively smaller difference due to the adoption than was the case with the total costs.

8.3. Impact of equipment costs

Changes in the costs of the equipment will be reflected in the final costs of the solution. The costs of the customer premises equipment can, especially due to the wide spread of the customer equipment be an important aspect in this change. In this study we varied the costs of the CPE from 50% of its original cost up to 150% of its original cost and checked the impact of this on the final cost of the network rollout. Clearly the impact will be reduced due to the large cost of the PIP network installation. Figure 72 gives a view on the relative costs on a per customer basis for the solution with a change in the CPE cost. In this figure one can clearly see the impact of the architectures with a lower CPE cost, which will be typically lower than the impact of those architectures with a higher CPE cost. Also interesting to note is how the impact of a higher CPE cost will be more pertinent in those architectures with a lower OLT equipment cost, as is the case in the HPON 40. This effect is especially apparent in the comparison to the HPON 40 architecture. Finally the model seems at first sight to react more or less linearly with the costs of the CPE equipment and fully symmetric in positive and negative cost change (+50% ~ -50%).

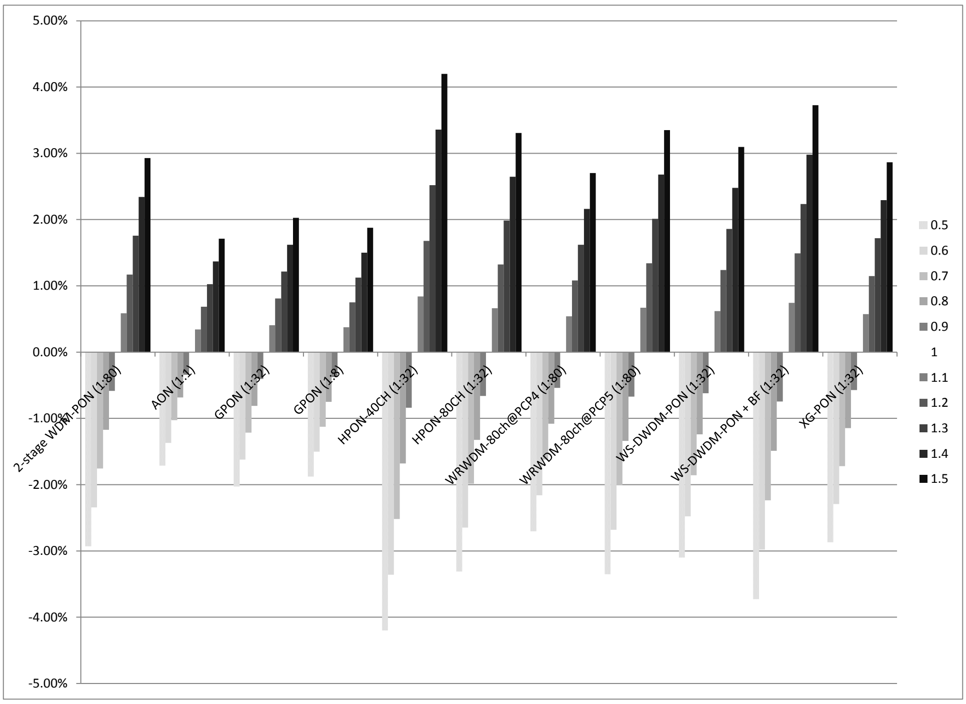


Figure 72: impact of the cost per customer for differences in CPE cost, relative on a per architecture basis to the situation with the original CPE cost.

In addition to the CPE cost, also the OLT cost has been taken into consideration in this sensitivity analysis. Figure 73 shows the impact on the total cost of the solution for changes on the OLT cost. We again changed the OLT cost from 50% of the original cost up to 150% of the original cost with steps of 10%. All solutions have a lower variation in their final cost for changes in the OLT cost than the variations we found in the case of the CPE variations. Clearly the solutions with a passive splitter solution at a high split rate have a very low variation for changes in the OLT cost. Total cost variations are very limited when looking at the total cost.

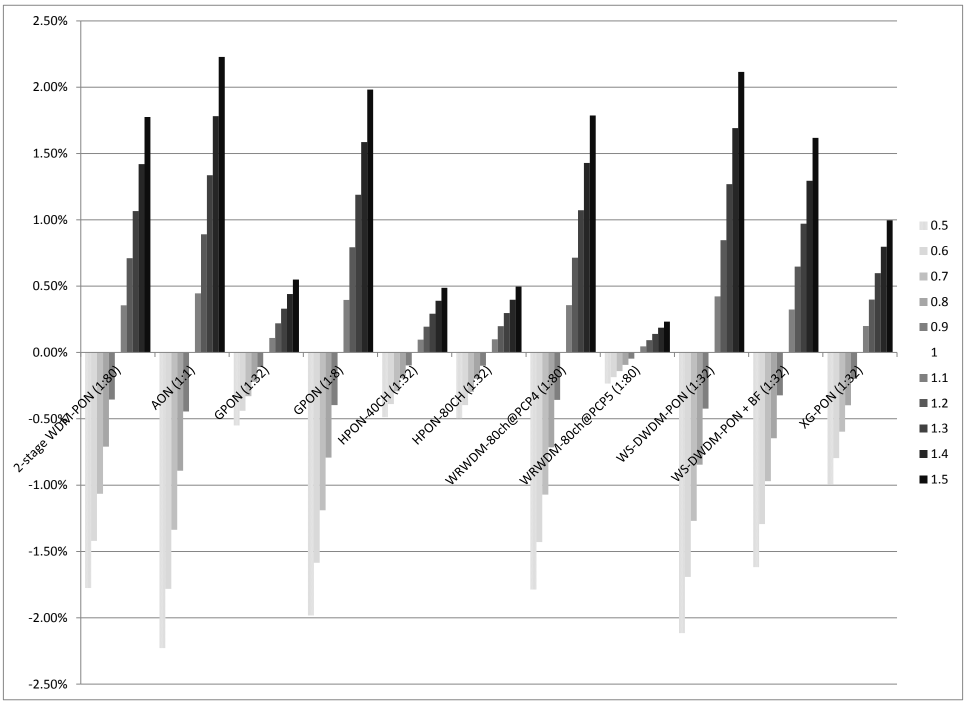


Figure 73: impact of the cost per customer for differences in OLT cost, relative on a per architecture basis to the situation with the original OLT cost.

8.4. Impact of adoption rate

Adoption is one of the main impacting parameters in any business case, and in the case of an NGOA and the calculations within TONIC, we take a closer look at the impact on the total cost of changes in the adoption rate. We changed the adoption rate both in speed as in starting adoption, which is often a parameter at which alternative operators will aim by means of pre-subscriptions or communal rollouts. The figures below give a view on the impact on the total costs of both parameters.

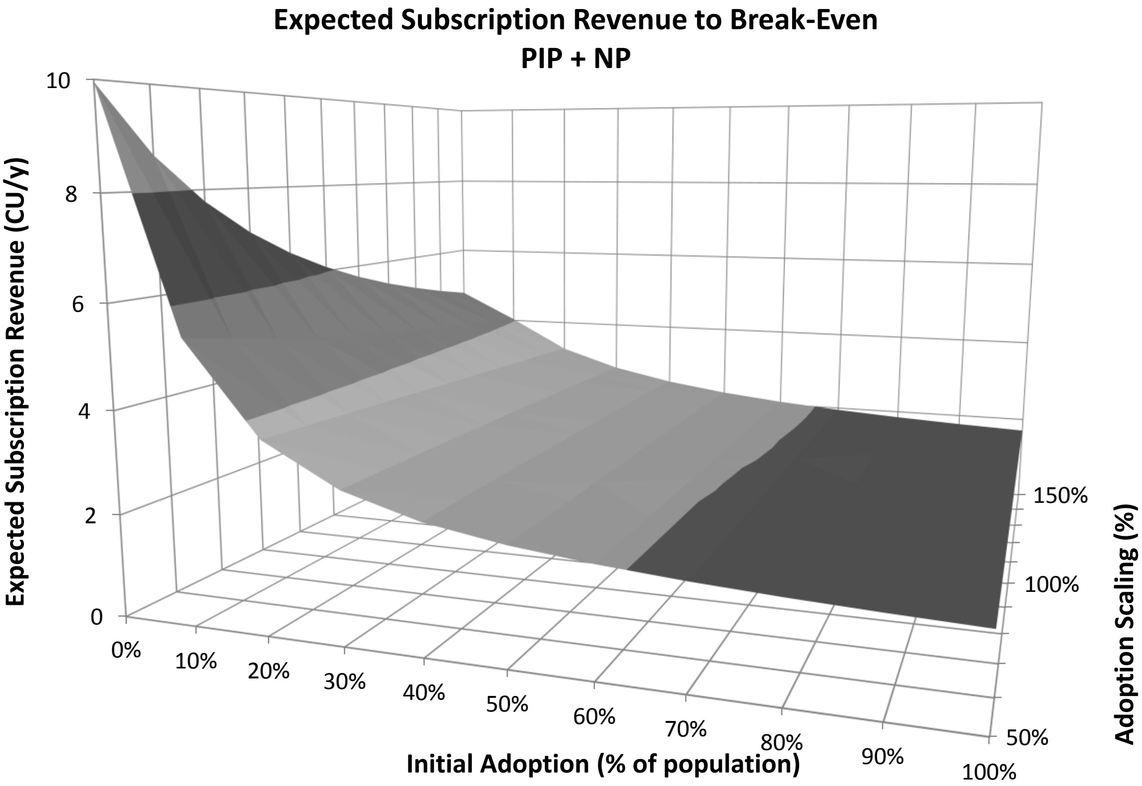


Figure 74 Expected revenues per subscription to reach breakeven PIP+NP

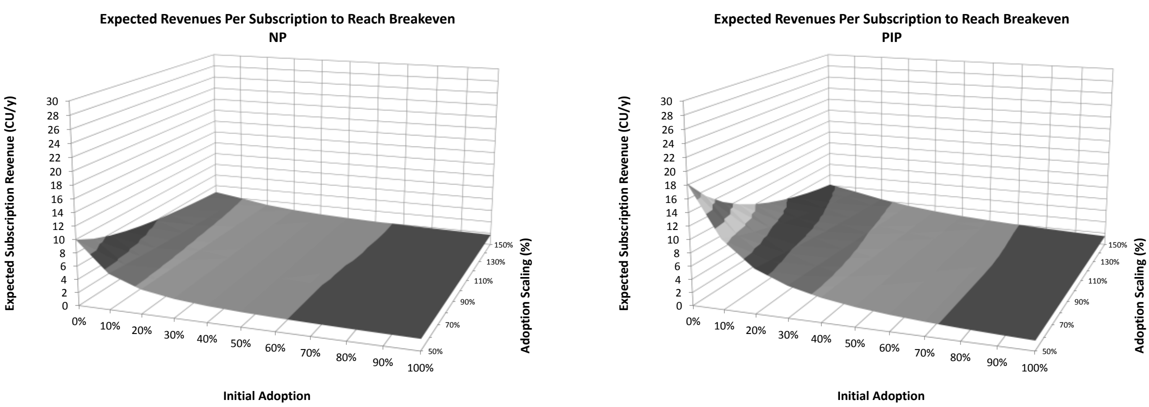


Figure 75 Expected revenues per subscription to reach breakeven PIP (left) and NP (right)

We have shown all costs in a discounted manner and per subscription, as adoption rate and the amount of initial adoption will have an important impact on the timing of the costs and on the rate at which they can be repaid. Not taking the cost per subscription into account would give an incorrect view as a high adoption will increase the costs, but on the other hand will most probably render a more profitable business case. Looking at the cost per subscription we clearly will see how a larger adoption will lead to lower expected revenue per subscription. Not taking discounting into account would also give an incorrect view as a high initial adoption will clearly lead to higher amount of subscriptions and as such to a lower expected revenue per subscription, while on the other hand it will also lead to a higher upfront cost and as such have a negative effect on the expected revenue per subscription.

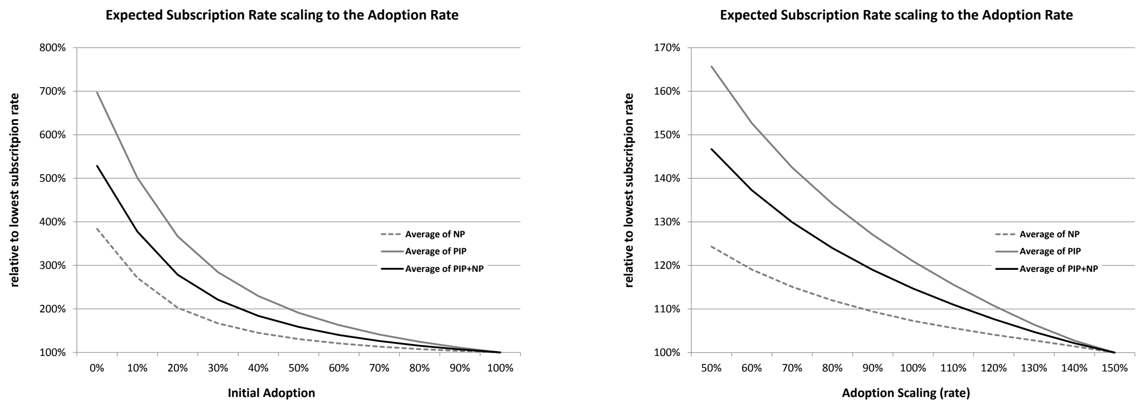


Figure 76 Expected subscription rate scaling to the initial adoption rate (left) and adoption rate (right)

The figure clearly shows how an increase in the initial adoption comes with a very steep decrease in the expected subscription rate. The effect of an increase in the adoption rate (scaling) is also a steep decrease in the expected subscription rate. This combines to an asymptotically decreasing curve for increases in one or both these parameters. The additional smaller figures of the PIP and NP part of this cost show how the NP is only little impacted by changes in those two parameters. The NP is less impacted by changes in both parameters than the PIP and as such the overall cost impact is found in between that of the NP and PIP. The following effects might be in play to come to this result: (1) most PIP costs have to be made in advance, regardless of the actual adoption. As such a higher adoption will easier cut the revenues required, e.g. dividing the same costs by twice the amount of customers will clearly reduce the required subscription revenues by half. This is in contrast to the costs of the NP which can be for a larger part made as customers come in the network. This might not be equally important for all the architectures considered in this analysis. (2) A lower discount rate will make the effect of early adopters more pronounced as the revenues they generate contribute for more over a longer period of time. The PIP which has a 5% discount rate in this analysis (as discussed with WP6) will as such favour the initial adoption much more than the NP which has a 10% discount rate.

9. Conclusion and guidelines

This deliverable presents the cost analysis of different NGOA architectures.

The first cost assessment has been performed considering a migration from an existing traditional optical access solution (such as GPON or AON) in a non-node consolidation scenario. The cost assessment shows that the architectures have higher a OPEX than CAPEX when summing the costs from 2020 to 2030 (NGOA operational time) for any type of area (i.e. DU, U and R). The most costly architecture is the UDWDM for any area, whereas the less costly solution is to keep existing optical access networks and upgrade existing GPON by reducing the splitting ration from 32 to 8 so that the bandwidth increases or to keep the AON as it is. The CAPEX key cost factors of these architectures differ: for UDWDM is NP and CPE equipment, for AON is the NP equipment and in-house infrastructure, whereas for the GPON upgrade is CPE and in-house infrastructure. Regarding OPEX, the most important factor is the service provisioning. The impact of energy and FM differs significantly on the architecture (e.g. UDWDM has high energy and FM but relatively low CPE energy cost; AON has low CPE related costs; whereas GPON has lower values but slightly higher CPE energy cost).

When considering node consolidation, multiple architectures have been evaluated since they can offer the long reach requirements while keeping the high bandwidth per user. In this scenario, it can be observed that the upgrade of GPON by reducing the splitting ratio is not an option due to the high costs related to the new LL5 links (increases more than 1 CU/year per user). Some architectures keep and even decrease their average TCO per user per year when applied to aggressive node consolidation scenarios: e.g. HPON40 (for any area) and WSWDM PON (for DU) solutions. Furthermore, the options to connect AON AS with a WDM Backhaul, or migrate from GPON to HPON architecture are the most effective solutions for any type of area applying node consolidation. It has to be mentioned that extra savings could be expected on the reduction of cost due to liberation of central offices as well as on the concentration of A/C and Power systems, which have not been included in the study due to missing data.

In an NP brownfield scenario, the cost key factors that have been identified are: the SP and any related CPE parameter such as cost, energy consumption (and failure rate which is related to the FM that includes the replacement of the CPE).

The migration for most of the studies has been assumed to start in 2020 and last one year, which is a realistic for one area and cost estimations can be extracted when no discounted values are considered. However, the impact of the duration of the migration has been evaluated by comparing the results with a longer migration of 3 years for the particular case of GPON to HPON migration scenario. The conclusion is that a longer migration process softens the cost peaks of ONT cost and SP, while having small impact to the other cost parameters. Furthermore, a later migration impacts significantly the ONT and SP cost since the later the migration starts, the more users need to be migrated and hence, higher investment in terms of CPE and SP.

The impact of duct availability (related to the possibility to have a greenfield or more brownfield PIP) on the infrastructure cost differs on the architecture and on the area: higher for DU than rural areas, higher for AON P2P and WRWDM PON than HPON solutions.

Finally the sensitivity analysis has rendered us with a more detailed view on what happens when the main influencing aspects in the context of the network rollout are changed. These led to the following results:

- A higher fanout will for all architectures lead to a lower cost per home passed and to a lower overall cost. Cost reductions up to 30% and more are reachable by increasing the fanout substantially. It should be noted that the higher fanout cases might conflict with the consolidation possibilities – as a higher fanout will reduce the reach – and maximum dedicated bandwidth – as with a higher fanout, more customers are sharing the same OLT port. Relaxing the OASE requirements – for instance only in an initial phase – could as such reduce the upfront costs substantially
- Regional differences could lead to a very different cost of deployment. Especially in those European countries with lower average salaries, the costs could be much lower. Next to the salary, the adoption is the most important impacting factor and a higher adoption will lead to a lower cost per customer in the end.
- The impact of costs of the ONT and OLT equipment behaves more or less linear for all architectures and has a rather limited impact up to resp. ~5% or ~2% for an increase up to 50% of its original cost.
- Adoption has most probably the highest impact of all factors and has been split into initial adoption effect (e.g. by means of presubscriptions) and the steepness of the adoption curve. Increases in the initial adoption lead to the most substantial decrease in the cost per subscription year. Still the effect of having a faster adoption is certainly very important.

Appendix: Urban cost assessment

Non-node consolidation

This section presents the results for an urban area. It can be observed that the cost values are intermediate values of the results obtained for dense urban and rural areas presented in Section 4.3.

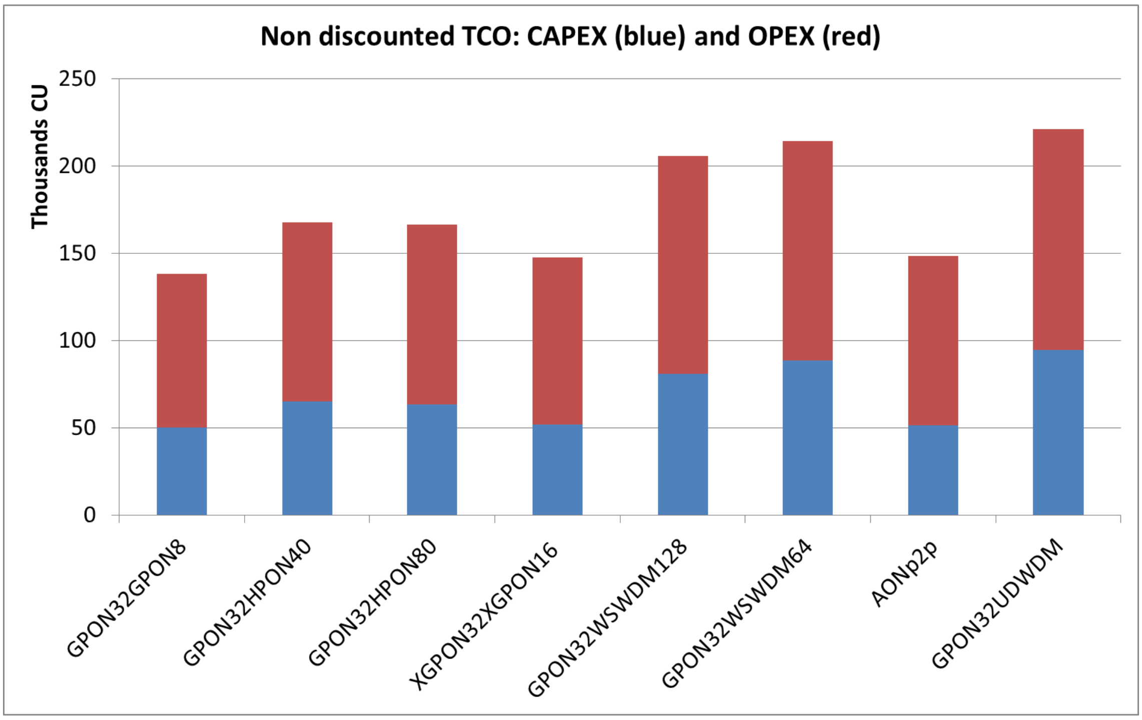


Figure 77 Non discounted TCO in urban areas (non-node consolidation)

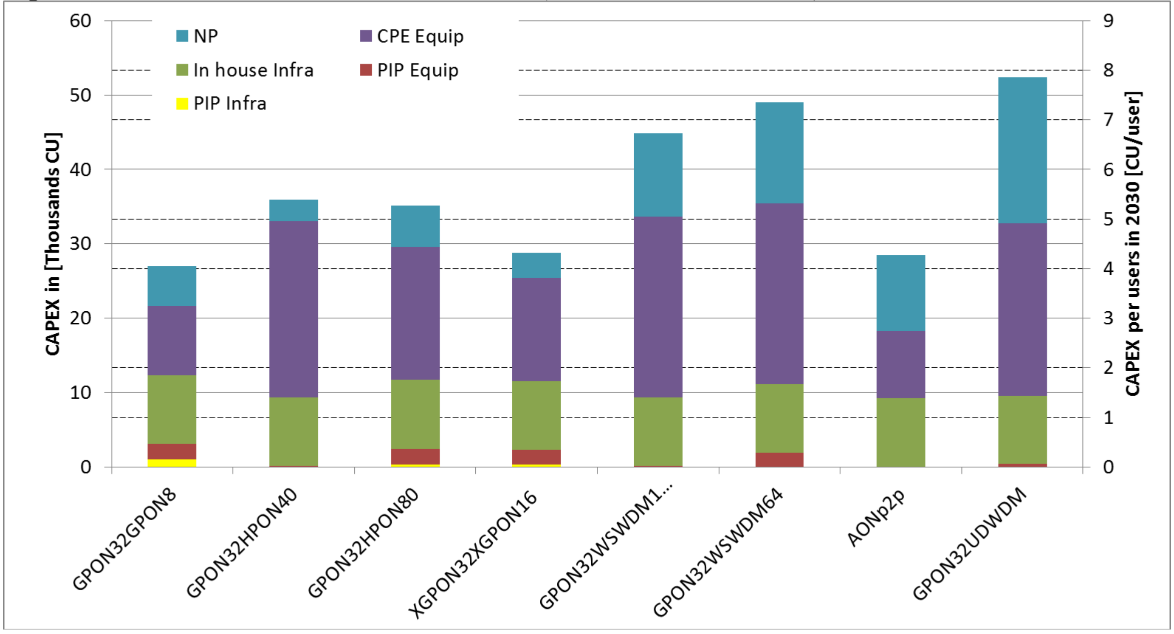


Figure 78 Total CAPEX [CU] of the left axis and CAPEX per user [CU/user] on the right axis of different NGOAs in urban area with non-node consolidation

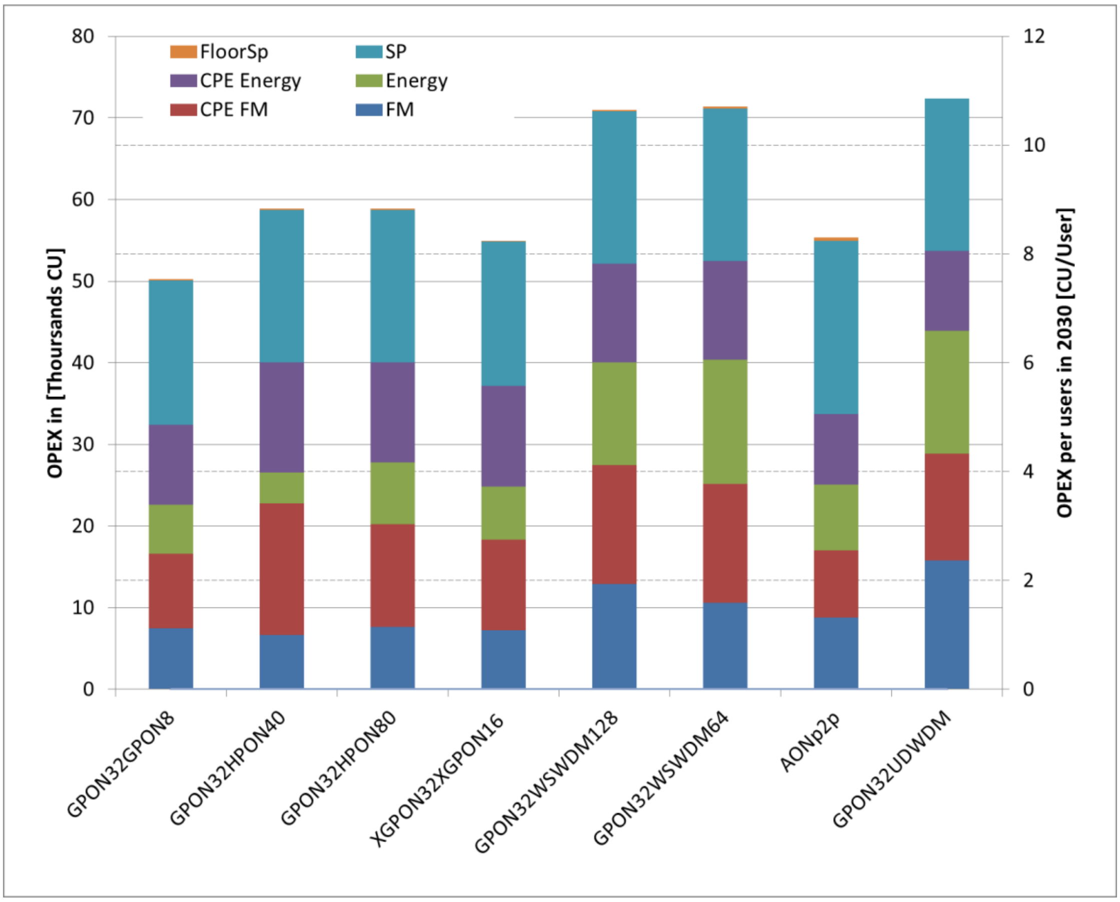


Figure 79 Total OPEX [CU] (left axis) and OPEX per user (right axis) in urban areas with non-node consolidation

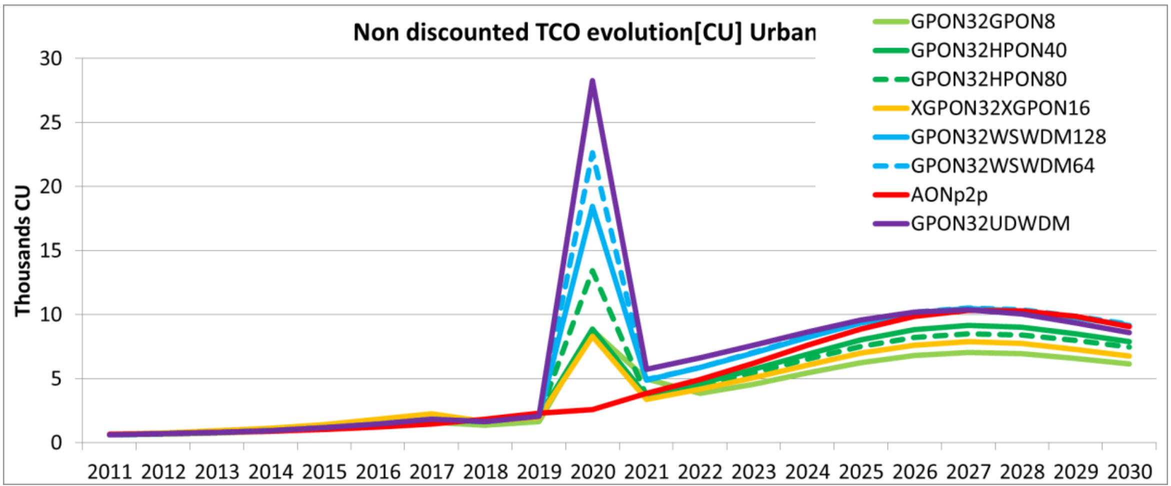


Figure 80 Non discounted TCO [CU] per year in urban areas with non node consolidation

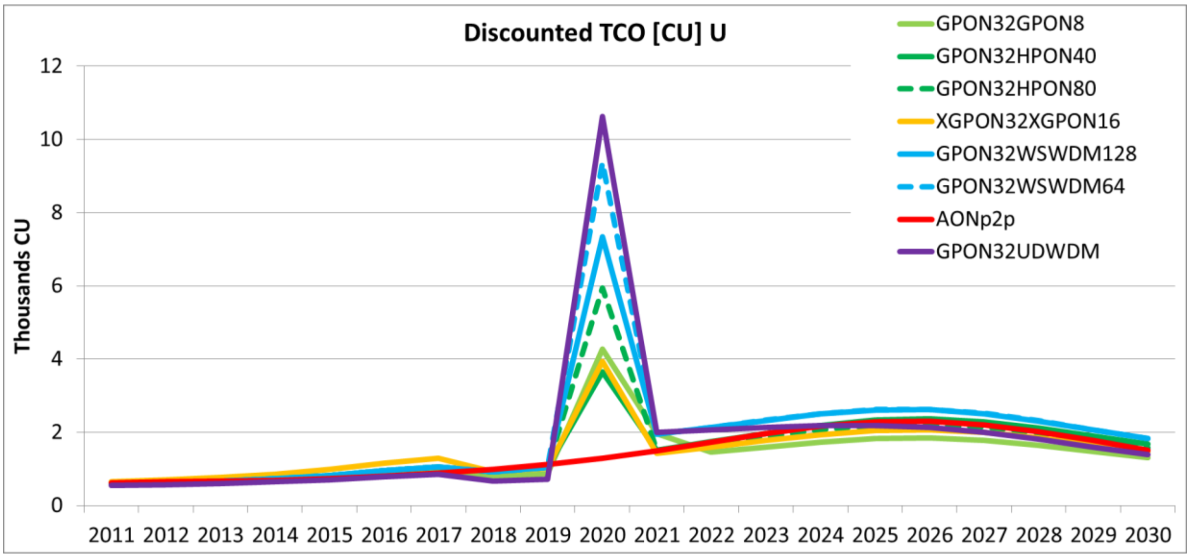


Figure 81 Discounted TCO[CU] per year in urban areas with non-node consolidation

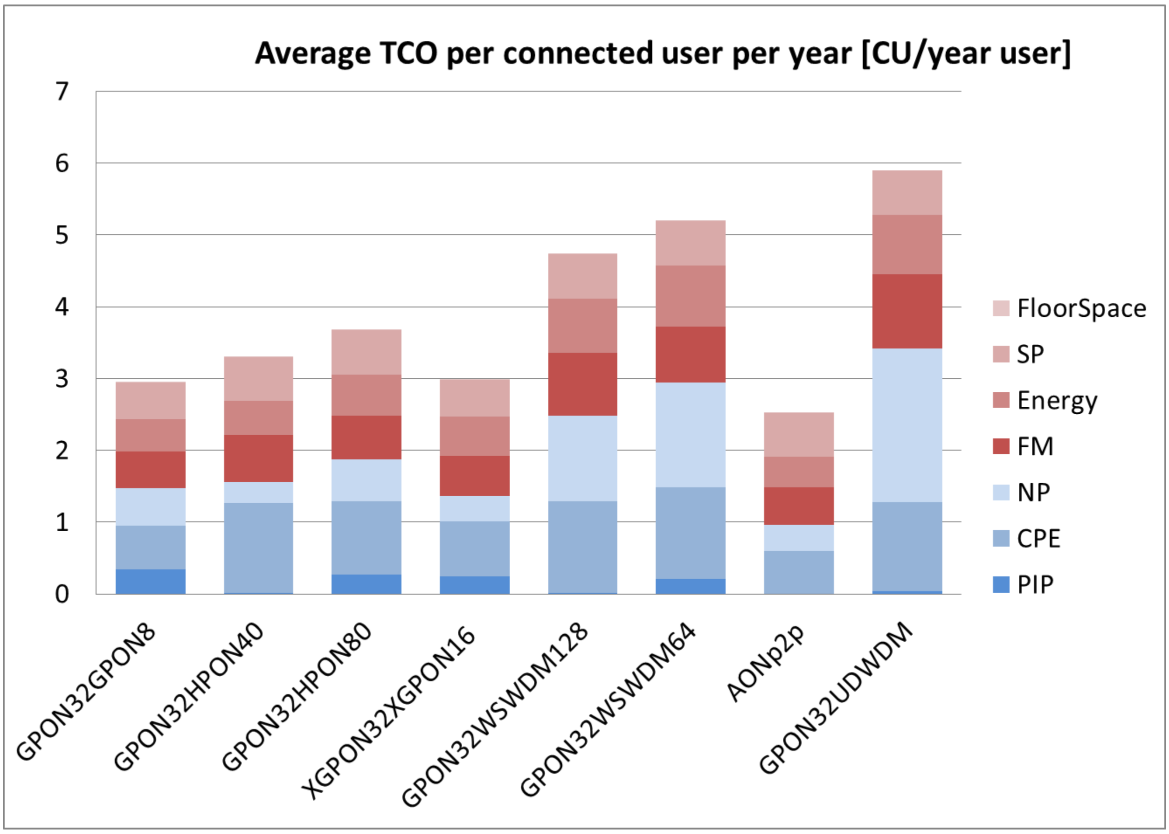


Figure 82 Average TCO (CAPEX components in blue and OPEX components in red) per connected user per year in urban areas)

Aggressive node consolidation

This section presents the results for an urban area. It can be observed that the cost values are intermediate values of the results obtained for dense urban and rural areas presented in Section 4.4.

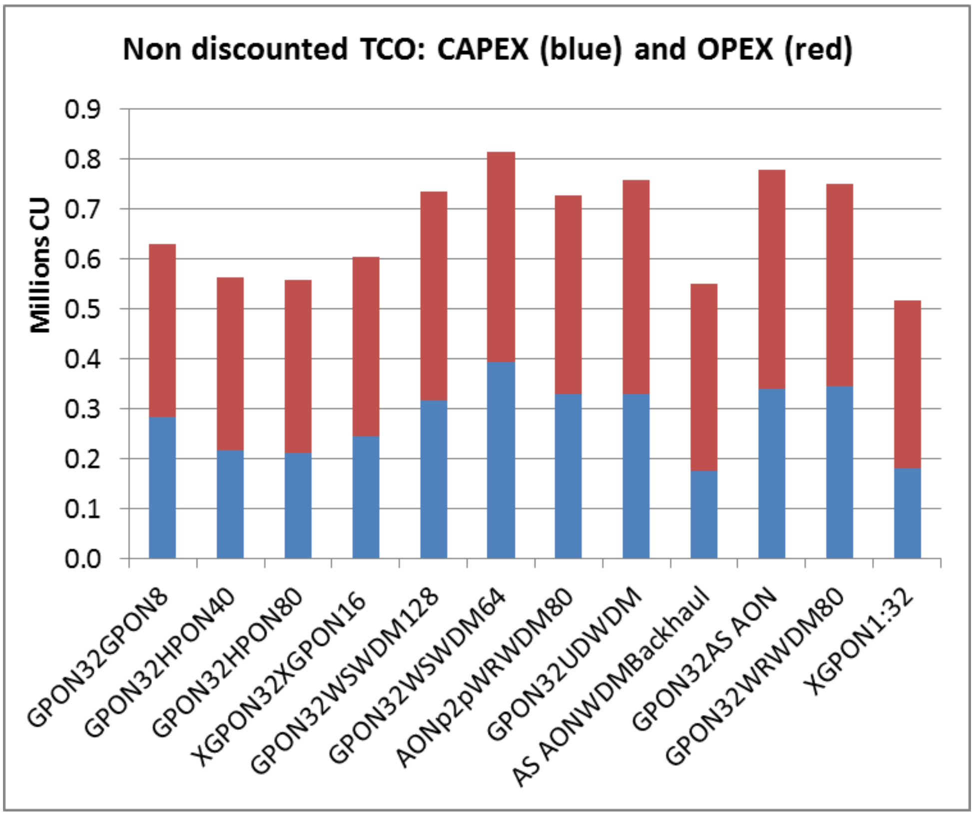


Figure 83 Non discounted TCO for urban areas with aggressive node consolidation

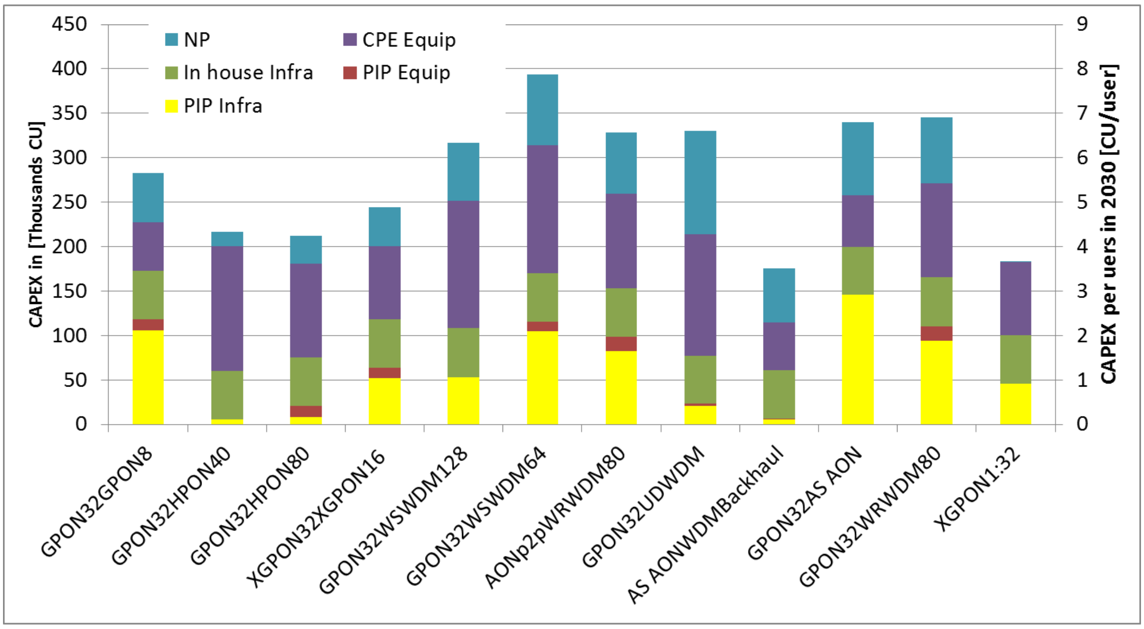


Figure 84 Total CAPEX [CU] of the left axis and CAPEX per user [CU/user] on the right axis of different NGOAs in urban area with aggressive node consolidation

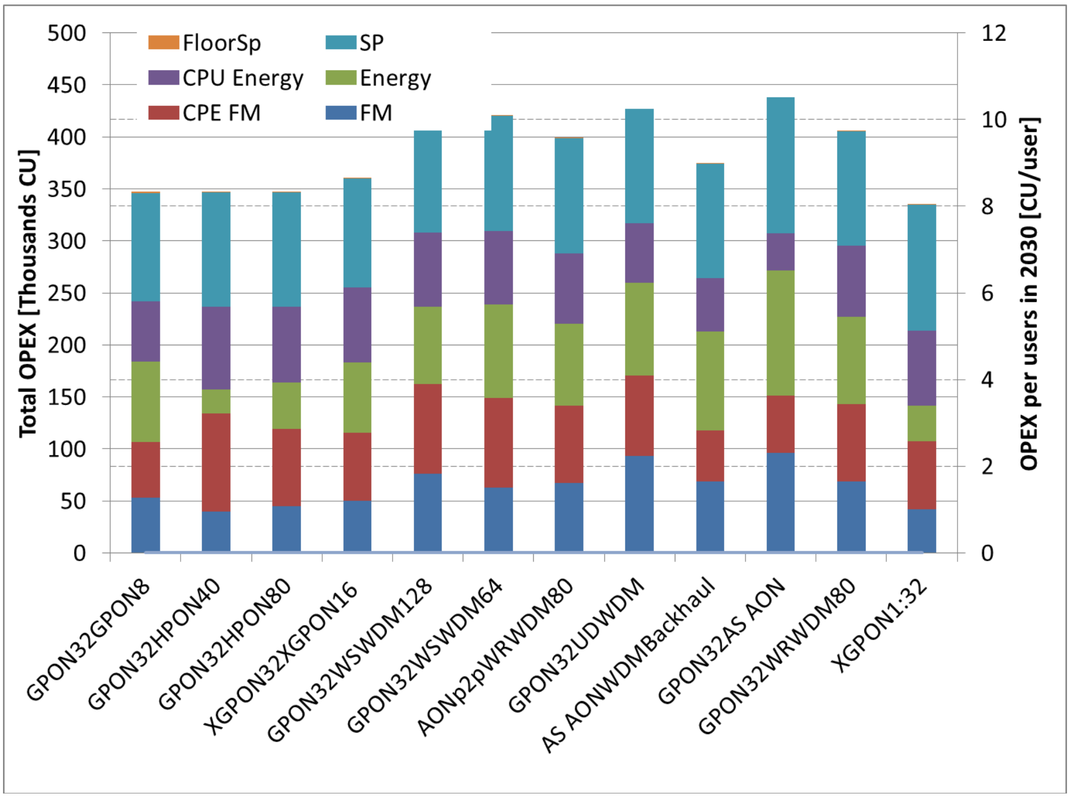


Figure 85 Total OPEX [CU] of the left axis and OPEX per user [CU/user] on the right axis of different NGOAs in urban area with aggressive node consolidation

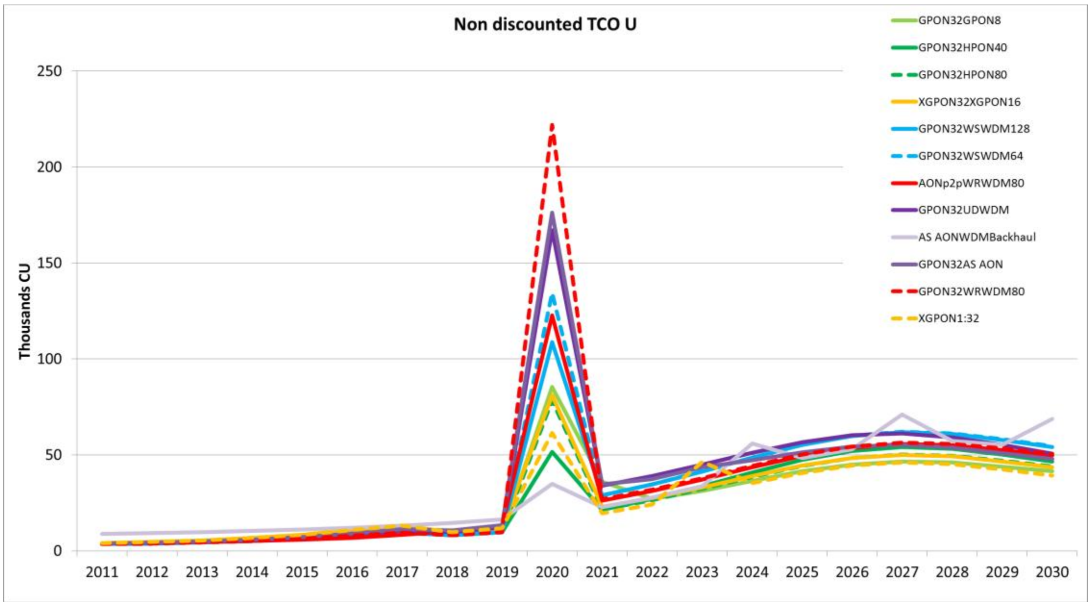


Figure 86 Non discounted TCO [CU] per year in urban areas with aggressive node consolidation

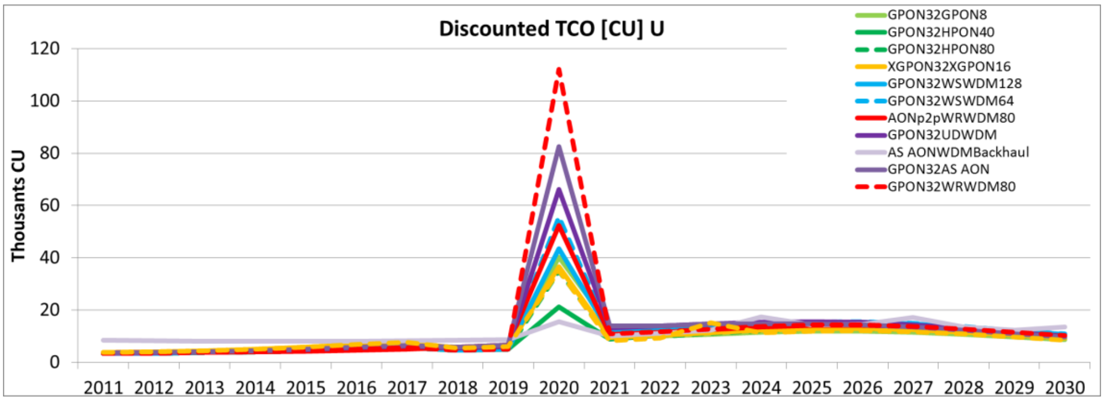


Figure 87 Discounted TCO [CU] per year in urban areas with aggressive node consolidation

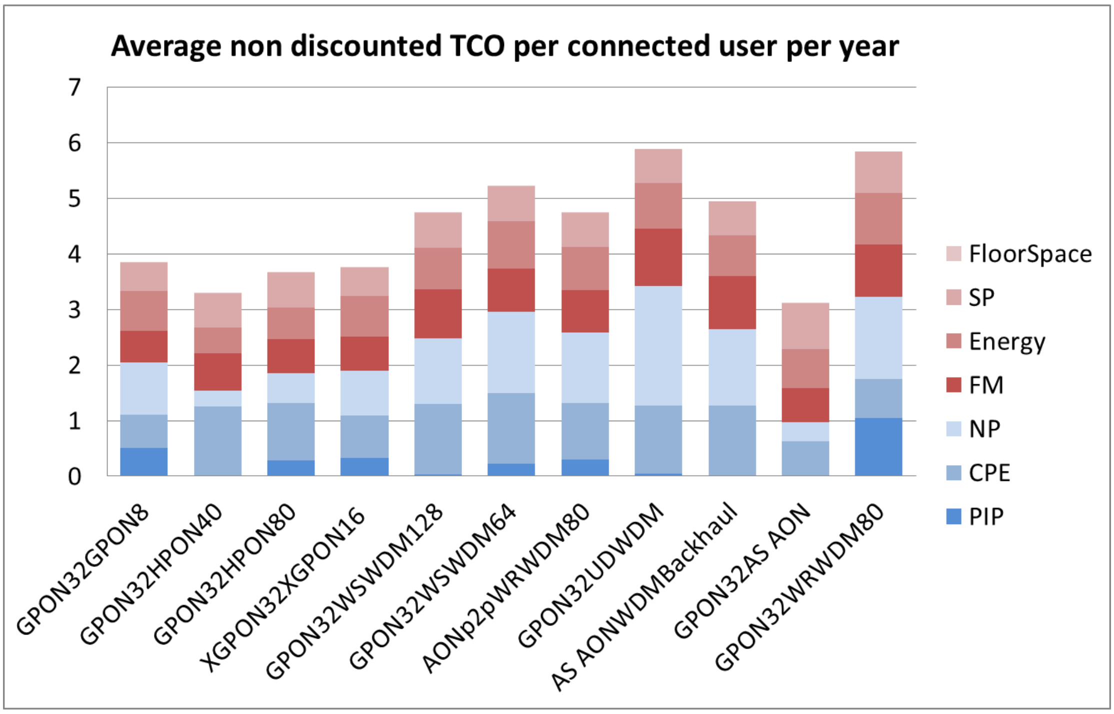


Figure 88 Average TCO (CAPEX components in blue and OPEX components in red) per connected user per year in urban areas).

Appendix B: Assumptions of cost assessment

This section summarizes some assumptions considered in the cost assessment:

Fault Management

As presented in D5.2, the fault management process consists of three main parts: pre-processing of the failure, failure reparation and post-processing of the reparation. The fault management process is triggered by the number of expected failures of any of the network components (either equipment or infrastructure), which is given as FIT rate.
The pre-processing includes the detection, help desk, opening TT, etc. and has been assumed to the same for all failures.
The reparation of the failure depends on the network component that has failed. Each network component has associated an average reparation time (MTTR), a travelling time to the failure location and the number of required technicians. The only exceptions are the ONTs since in these cases, no technician is associated to the ONT reparation, but rather a new ONT is shipped to the user.
The post processing of the reparation, which includes any required test and the TT closing is also assumed to the same for all failures.

Aggressive node consolidation

When applying the network dimensioning to the aggressive node consolidation, the required LL5 is computed considering that 50% of the trenching and duct is required. The number of LL5 fibres is calculated based on the number of PCP5s that have to be connected to the new OLT location (PCP6). However, these LL5 fibres are grouped into different ducts based on the aggregation factor of each case (i.e. how many traditional access areas are grouped into one new consolidated area).