Modeling the Lifecycle Greenhouse Gas Emissions of a Hybrid Satellite System

David Faulkner[1(✉)], Keith Dickerson[1], Nigel Wall[1], and Simon Watts[2]

[1] Climate Associates Ltd, 1 Westland Martlesham Heath, Ipswich IP5 3SU, UK
davewfaulkner@gmail.com, keith.dickerson@climate-associates.com, nigel.wall@shadow-creek.co.uk
[2] Avanti Communications Ltd, Cobham House, 20 Black Friars Lane, London EC4V 6EB, UK
Simon.Watts@avantiplc.com

Abstract. The aim of this paper is to present the approach used to model the greenhouse gas emissions of a hybrid broadband terrestrial/satellite system over its lifecycle. The lifecycle analysis showed that the electricity used by the customer premises equipment was responsible for the majority of the GHG emissions, assuming that the power plants continue to use fossil fuels. Emissions from manufacture, transport and waste treatment represented only 0.00453 % of the total emissions. Under a 1 % cut-off rule only the in-use emissions from on grid electricity would need to be considered. Manufacture, transport, and waste treatment can be safely ignored. This includes emissions from the manufacture of the satellite launch vehicle and the transport of the satellite into geostationary orbit.

Keywords: Hybrid satellite systems · Broadband Access · Energy-efficiency · Environmental assessment · Greenhouse gas emissions · Lifecycle

1 Introduction

Hybrid satellite networks combine different types of communications paths to provide a service. The EU 7th Framework Programme 'BATS' project (Broadband Access via integrated Terrestrial and Satellite systems) proposes such a hybrid system aimed at proving coverage to Europe at 30 Mbit/s with emphasis on rural areas which are unlikely to be well-served by terrestrial-only solutions.

Other publications concerning the environmental impact of this system focus on perspectives such as a comparison of the BATS solution with possible alternative terrestrial-only systems over the lifecycle [1]. In this paper we focus on how the inventory was produced, what emissions factors were used and what assumptions were made. The methodology used to carry out the environmental assessment was based on life cycle analysis (LCA) standardised by ETSI [2] with the ITU methodology [3] used

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to provide more detailed guidance where needed. The model is described in some detail so that the parameters which have most impact on the overall emissions can be identified and so that steps can be taken to minimize emissions. At the outset of this project we had no idea of the relative importance of the different lifecycle stages which include: raw material extraction, manufacturing, transport, use-phase and waste treatment. The life-cycle analysis (LCA) includes the launch vehicle which was chosen to be Ariane 5 as an example. The use-phase was considered to be important as it operates over the full 16 year life of the BATS system using on-grid electricity, which in most European countries is dominated by the burning of fossil fuels. These release greenhouse gases (GHGs) such as carbon dioxide (CO_2) into the atmosphere. The aim of this report is to explain how an LCA was carried out with focus on the hybrid satellite network elements and to show the relative importance of the life cycle stages.

2 System Boundary and Identification of Network Elements

The system boundary for carbon accounting is shown in Fig. 1. Note that the components of the hybrid satellite system are depicted in red. The terrestrial system, for example ADSL, is assumed to be already in place when the satellite system is added. The emissions associated with the construction of the terrestrial system are therefore excluded from the model, although the user modems (both satellite and ADSL) energy are taken into account.

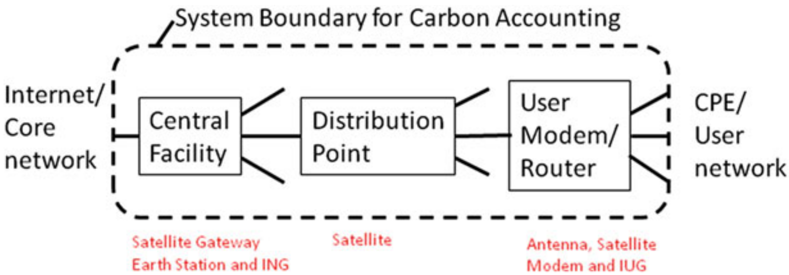

Fig. 1. Identification of network elements and system boundary

The network elements include: Satellites (GEO), Central Facilities added for BATS, Intelligent Network Gateway (ING), Earth stations including antenna, User satellite router including upstream power amplifier and power supply, Intelligent User Gateway (IUG), a home gateway which includes the terrestrial modem(s), and power supply. A system Block diagram is shown in Fig. 2. Note that the ING is shown as Integrated Core Network.

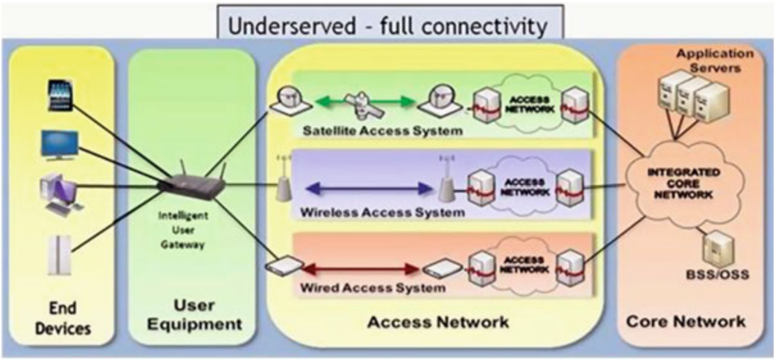

Fig. 2. Identification of network elements

3 Addressable Market

A key parameter is the number of terminals added and in operation each year which is equal to:

Number of households x take rate x market share for BATS x market annual profile.

The addressable market for rural services in Europe used in this analysis is shown in Fig. 3 where the blue bars represent households and the red bars the number of small businesses.

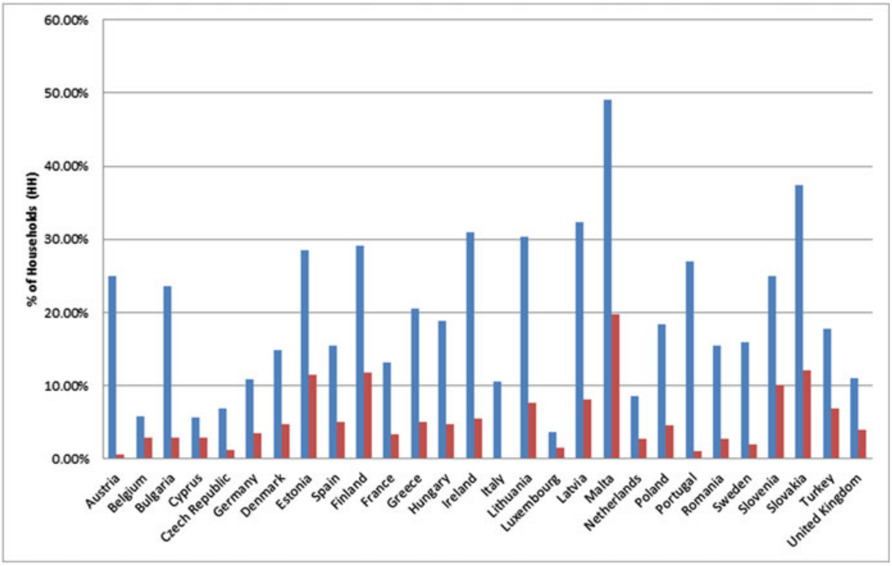

Fig. 3. Addressable market for 30 Mbit/s services in year 2020 (Color figure online)

It was calculated from Fig. 3 that, on average, 14.4 % of households in the EU27 countries plus Turkey will have satellite (shown in blue) as the only available technology for contracting broadband services at 30 Mbit/s or more. However, the average percentage of total households which will take up a satellite broadband connection is 3.72 % (shown in red), which are mostly located in remote areas.

The number of households in Europe (E28 plus Turkey) over the Period 2020–2035, the projected life of the BATS system, was estimated using references [4–7]. An analysis of these references showed that the expected number of households in year 2020 would be 245.5 M and a growth rate of 0.41 % per annum could be expected. The take-up rate annual profile (timeline) assumed is shown in Fig. 4.

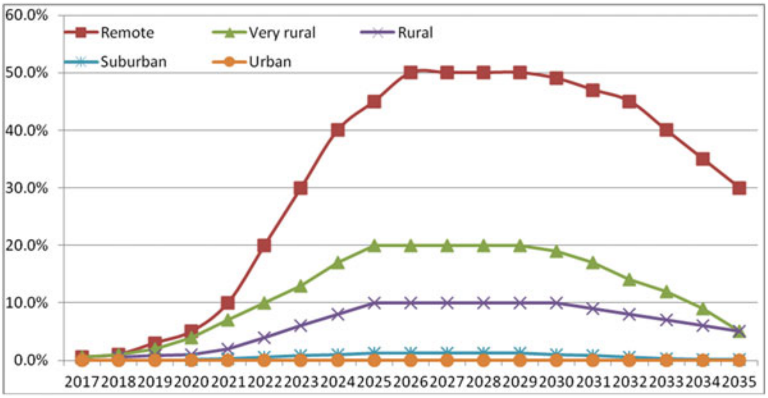

Fig. 4. Take-up annual profile for BATS services

It is assumed that the take up rate for BATS services versus other technologies such as satellite-only is 50 %. In the GHG emissions model the peak number of households taking BATS services was calculated to be 6.4 M households in year 2029.

4 Emission Factors

Emissions factors are parameters are normally provided by tables which when multiplied by a value attributable to a network element such as energy in kWh, weight in kg or distance travelled in km produce a value of carbon dioxide equivalent (CO_2e) emitted in kg. In some cases no emission factor could be found in tables or other references, such as the manufacture and combustion of butadiene which is used as a binder in the solid fuel booster. In that case estimates were made from first principles.

4.1 Electricity

A key emission factor is that of electricity. The GHG emission factor of electricity supply each year for the EU will vary over the period 2020–2035. The report “EU

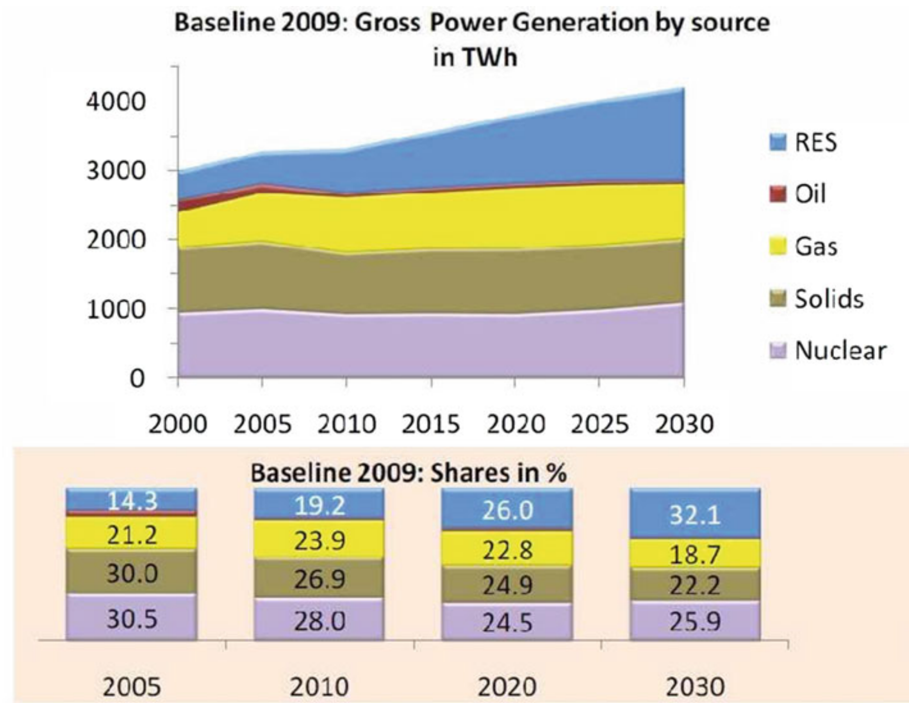

Fig. 5. Gross power generation by source (Europe) [8]

Energy Trends to 2030" provides a perspective of the energy source mix [8] over the life cycle of the BATS deployment.

From Fig. 5 the annualized decrease in fossil fuel is 0.75 % between 2020–2030. This trend is assumed to continue until 2035. The average GHG conversion factor for the EU in 2013 is given as 0.34723 kg CO_2 per kWh [9]. This was treated as the base year from which subsequent conversion factors are derived. In 2020 Fig. 5 shows that the proportion of fossil fuel is predicted to have fallen from 51.8 % to 49.5 %. The emission factor will then have fallen pro-rata to $0.34723 \times 49.5/51.8 = 0.33181$. Linear interpolation was used to derive the emission factors for each year over the period 2020–2035.

5 Life Cycle Stages of the Network Elements

5.1 Satellite Payload and Launch Vehicle

The manufacture of the satellite system includes all the physical components including the launch vehicle its payload. In addition the emissions arising from combustion of the fuel used to take the satellite into geostationary orbit must be accounted for. This should be accounted for under the Transport phase of the life cycle.

To estimate the emissions due to manufacturing, tables [9] were used to obtain a carbon factor. In this case the weight (mass) was multiplied by the emission factor to arrive at a CO_2e value in kg.

The Ariane 5 launch vehicle has a Gross Take Off launch capacity of 10,000 kg (22,000 lb.) for dual payloads or 10,500 kg (23,100 lb.) for a single payload [10]. The emissions of the launch vehicle were therefore scaled according to the actual payload (6400 kg) assuming a second load is carried.

The launch vehicle mass includes the main stage the upper stage, the solid fuel boosters, the payloads and the propellants.

Hydrogen and oxygen are the two chemicals used in the cryogenic main engine. The masses are 133 and 26 tonnes respectively. These react to produce water which is not classified as a GHG. No account is taken of the impact of water emission into the stratosphere. Note that this reaction would be in the transport phase of the life cycle as the satellite is transported to its geostationary orbit. Account is taken of the emissions incurred during manufacture of propellants. Details of the manufacture of liquid oxygen are given in Reference [11]. The conversion factor is 0.310 kWh/kg. Details of the manufacture of hydrogen are given in [12]. The conversion factor is 8.5 CO_2e kg/kg.

The emission due to the manufacturing and transport of the solid fuel booster was calculated from the mix of its chemical constituents which include a propellant mix of 68 percent ammonium perchlorate (oxidizer), 18 percent aluminium (fuel), and 14 percent polybutadiene (binder) is used in the solid rocket motors. Reference [13] states: The chemistry of the solid rocket booster propellant can be summed up in this reaction:

$$10\ \mathrm{Al} + 6\ \mathrm{NH_4ClO_4} \rightarrow 4\ \mathrm{Al_2O3} + 2\ \mathrm{AlCl_3} + 12\ \mathrm{H_2O} + 3\ \mathrm{N_2}$$

The CO_2e emission arising from the manufacturing solid fuel boosters was estimated by consideration of the detailed manufacturing processes of each chemical multiplied by their molecular weights. The chemicals included: aluminium (both as a fuel and in the tank casings), ammonium perchlorate, hydroxyl-terminated polybutadiene (binder). Boosters are fabricated from 62 tonnes steel.

The CO_2e emissions arising from the launch of Ariane 5 may be considered as the transport phase of the life cycle. The reactant products are not classified as greenhouse gases by the IPCC. They are emitted as a white powder. In the stratosphere they are likely to reflect direct sunlight and so may have an overall cooling effect. However they may trap infrared radiation and have a warming effect. More research is being carried out to measure the overall impact on surface temperature.

The second reaction arising from the solid fuel booster may be estimated from the combustion of 1-3 Butadiene (C_4H_6) binder. It is assumed this short chain dominates but longer chains exist in the binder.

$$\mathrm{C_4H_6} + 11\mathrm{O_2} \rightarrow 4\mathrm{CO_2} + 3\mathrm{H_2O}$$

The mass of polybutadiene was calculated to be 66.6 tonnes. From consideration of the molecular weights the mass of CO_2 ejected is 217 tonnes per launch assuming all the binder is consumed. No account was taken of the waste treatment as no parts of the Ariane 5 are recovered. The environmental impact of steel in seawater was assumed to be negligible.

5.2 Ground Segment (Earth Station) Life Cycle Parameters

The ground segment includes: Antenna, high power amplifier (HPA), frequency convertors, electronics for control and management and air-conditioning.

Table 1. Breakdown of parameters for satellite gateway

ID	Component	Wt (kg)	Pwr (W)	QTY	Tot wt	Tot pwr	Source
1	Antenna	2,500	15	1	2,500	15	http://comsatsystems.co.in/admin/?page_id=25
2	HPA	25	821	3	75	2,463	http://www.cpii.com/docs/datasheets/256/MKT-1511.pdf
3	Frequency convertors	7	60	21	147	1,260	GD Satcom, 10 uc 10 dc tc
4	Other BATS electronics	50	500	1	50	500	Estimate
5	Air con	150	8,000	0	0	381	In existing room with other services. 30% duty cycle assumed at PUE=1.3
	Total				2,772	4,605	

The breakdown of parameters for a single satellite gateway is given in Table 1. 38 of these are required throughout Europe.

It was assumed that the buildings already exist and that there is sufficient existing HVAC, UPS and standby generator capacity is sufficient.

The Earth Station manufacturing emissions were estimated from the incremental weight of 2772 kg multiplied by a carbon factor of 0.537 kg CO_2e per kg for WEEE – large [9]. The 2014 figure was used. It was assumed that the equipment and antenna are made mostly from aluminium.

Incremental installation activities include: site survey, installation of equipment and commissioning. Transport was assumed to be approximately 400 km. This would be via 10 visits per gateway in a light commercial van with a 40 km round trip. The emission factor of a light commercial van was estimated to be 0.164 kg CO_2e in year 2020 falling to 0.12 kg CO_2e in year 2035 [14].

The manufacturing emissions were estimated from the incremental weight of 10 kg (including modem cable and antenna) in kg multiplied by a carbon factor of 0.537 kg CO_2e per kg for WEEE – large [9]. The 2014 figure was used as the latest available.

The delivery vehicle for installation is assumed to be a light commercial van. 40 km was assumed initially (as for VDSL and fibre examples). However 15 % users are assumed adopt self-install. Therefore a nominal 40 km reduces to 34 km plus 2 km round trip for mail van delivery of the modem and IUG (final proportion of trip).

The waste treatment was calculated from the mass of the components multiplied by the conversion factor for WEEE [9]. The 2014 figure was used as the latest available. This was 2772 kg multiplied 0.021 kg CO_2e per kg.

5.3 Intelligent Network Gateway Lifecycle Parameters

A virtualised Intelligent Network gateway (ING) is envisaged in year 2020. This would be located at a data centre which may be part of the internet point-of-presence (PoP). The power consumption was estimated by taking the power consumption of a server of today and scaling it according to Moore's Law to year 2020. This was estimated at a power of 650 W and a maximum fan-out of 94081 in year 2020. To obtain an estimate of the energy used by the INGs the power per server was multiplied by the maximum number of user terminals (6.4 m) divided by the fan-out.

Upgrade of the terrestrial backhaul network between a satellite gateway and the PoP may be needed to cope with additional traffic. It is not thought that this upgrade would contribute significantly to the GHG emissions, so no allowance for this was included in the model.

5.4 User Modem Lifecycle Parameters

An average satellite modem power of 7.5 W was considered to be representative of hybrid satellite systems over the period 2020–2035 based upon a modem of peak power 22 W and the existence of standby modes which reduce the duty-cycle to around 30 %. The majority of the upstream traffic would be carried by the ADSL2 modem. Whereas downstream traffic will increase over the period, the upstream traffic is not expected to increase significantly. This is because illegal file sharing via peer to peer networking is changing to favour legitimate downloads using paid-for services.

The manufacturing emissions were estimated from the incremental weight 10 kg (including modem cable and antenna) in kg multiplied by a carbon factor of 1.149 kg CO_2e per kg weight of mixed electrical and electronic equipment [9]. The 2014 figure was used as the latest available.

It is assumed that user terminals are not replaced during the life of the BATS system and the waste is disposed of during the final year 2035. The conversion factor used was 0.021 kg CO_2e/kg, from the DEFRA 2014 sheet on 'waste treatment' [9].

5.5 Intelligent User Gateway

The Intelligent User gateway (IUG) is assumed to be functionally similar to a home gateway as described in Section C1 of the EU CoC for broadband equipment [15]. The power consumption target for 2015–16 may be estimated by summing the power consumption of the WAN interfaces (including the central processor and data storage) plus the LAN interface(s) as shown in Table 10. The average power consumption with cache was estimated to be 5.7 W. It is assumed that the manufacturing weight is similar to that of an ADSL modem. This was estimated to be 0.47 kg including power supply. The IUG was assumed installed along with satellite modem as described above. It is assumed that IUGs (and satellite modems) are not replaced during the life of the BATS system and the waste is disposed of during the final year 2035. The conversion factor used was 0.021 kg CO_2e/kg, from the DEFRA 2014 sheet on 'waste treatment' [9].

6 Model Structure and Operation

The model, an Excel spreadsheet which totals the GHG emissions over the life cycle which can be attributed to Europe (28 countries plus Turkey). It includes emissions within GHG protocol Scopes 1, 2 and 3 [16] (Fig. 6).

	A	B	C	D	E	F	G	H	I
1									
2	Year >>				2020				
3	**Calculation of market size**	value	Unit						
4	Growth rate of households	0.41	%		245500000				
5	Addressable market	14.4	%						
6	Take rate peak	35	%						
7	Addressable market annual profile % relative to peak at 100%	See>>	%		10				
8	Number of households with satellite broadband				1237320				
9	Number of BATS units operating based upon share of available sat	50	%		618660				
10	Number of Units added (or removed) in year				618660				
11	**Conversion Factors**								
12	Conversion factor-electricity	0.33181	kg CO2e per kWh				0.33181		
13	Conversion Factor - delivery vehicle (light commercial-van)	0.181	kg CO2e per km				0.164		
14	Conversion Factor - truck of capacity 3.5-7 tonnes	0.642	kg CO2e per km				0.6309524		
15									
16	**Network Elements and Processes**				Number	Number	Conversion	GHGe	
17					added	Operational	factor	kgCO2e	
18	**BATS network elements and processes**								
19	ING power average	42443	W		1	1	0.33181	1.23E+08	
20	ING manufacture	27	kg		1	1	0.53724	1.45E+01	
21	ING installation	1	km		1	1	0.164	1.64E-01	
22	ING waste treatment	27	kg		1	1			

Fig. 6. Screen shot of the EU GHG emissions model showing key input parameters

The names of key global parameters are entered in cells A4-A14 together with their base value (e.g. for year 2014) in cells B4-B14. Years (of BATS implementation) are shown in Cells E2 and J2 etc. Values for each year are separated by purple columns such as D and I. Key parameters such as number of households and conversion factors for electricity change gradually from year to year as fuel sources change. These have been estimated according to the best available publication or statistics and entered into

	A	B	C	D	E	F	G	H	CG
17					added	Operation:	factor	kgCO2e	
18	**BATS network elements and processes**								BATS
19	ING power average	42443	W		1	1	0.33181	1.23E+08	1.75E+09
20	ING manufacture	27	kg		1	1	0.53724	1.45E+01	1.45E+01
21	ING installation	1	km		1	1	0.164	1.64E-01	1.64E-01
22	ING waste treatment	27	kg		1	1			2.15E+01
23	Earth station (gateway) power	4605	W		19	19	0.33181	2.54E+08	6.96E+09
24	Earth station (gateway) manufacture	2722	kg		19		0.53724	2.78E+04	5.56E+04
25	Earth station (gateway) installation	400	km		19		0.164	1.25E+03	2.47E+03
26	Earth station (gateway) waste treatment	2722	kg		19				5.72E+01
27	Satellite weight	6400	kg		1		2.865	1.83E+04	8.55E+04
28	launch vehicle +payload manufacture	21417	kg		1		2.865	6.14E+04	1.23E+05
29	solid fuel booster casing manufacture	39680	kg		1		0.8623	3.42E+04	6.84E+04
30	launch fuel emission butadiene	138880	kg		1		3.26	4.53E+05	9.05E+05
31	launch fuel manufacture aluminium	27392	kg		1		2.865	7.85E+04	1.57E+05
32	launch fuel manufacture hydrogen	22016	kg		1		8.5	1.87E+05	3.74E+05
33	launch fuel manufacture oxygen	26387	kWh		1		0.33181	8.76E+03	1.74E+04
34	launch fuel manufacture chlorine	172848	kWh		1		0.33181	5.74E+04	1.14E+05
35	User satellite modem energy and power amplifier energy	7.5	W		618660	618660	0.33181	1.35E+10	1.45E+12
36	User satellite modem manufacture	10	kg		618660		1.149	7.11E+06	7.37E+07
37	IUG (user hub) power average	5.7	W		618660	618660	0.33181	1.03E+10	1.10E+12
38	IUG (user hub) manufacture	0.466	kg		618660		1.761	5.08E+05	5.26E+06
39	CPE Installation 1 visit in light commercial van	34.3	km		618660		0.164	3.48E+06	3.38E+07
40	User equipment waste treatment	10.466	kg						1.40E+06
41	Total BATS							2.41E+10	**2.56E+12**
								embodied	1.16E+08

Fig. 7. Screen shot of the BATS network element input parameters

the spreadsheet for each of the years 2020–2035. Extensive use was made of the comments field to show the source reference of a parameter value.

The network elements and processes are listed in Column A. Column B shows the parameter in kW, kg or km which is associated with carbon emissions for the network. The number added in year 2020 is shown in column E. The conversion factor to kg CO_2e is in Column H. These are obtained from tables or deduced from them according to the year of emissions.

The total BATS emission for the year 2020 (cell H41) is 2.41 E10 kg CO_2e (24.1 Mtonnes CO_2e). Each year is calculated similarly and is then totalized over the life cycle and plotted.

7 Results

Results appear in numerical form in kg CO_2e in the final column of the spreadsheet. This is column CG in Fig. 7 which shows totals the emissions for each category over the years 2020–2035. The total for the EU-28 plus Turkey is shown as 2.56 Gtonnes in cell CG41 (Fig. 8).

The most significant emissions may be attributed to the use of electricity measured in kWh over the 16 year lifecycle. This includes the earth station energy, user satellite

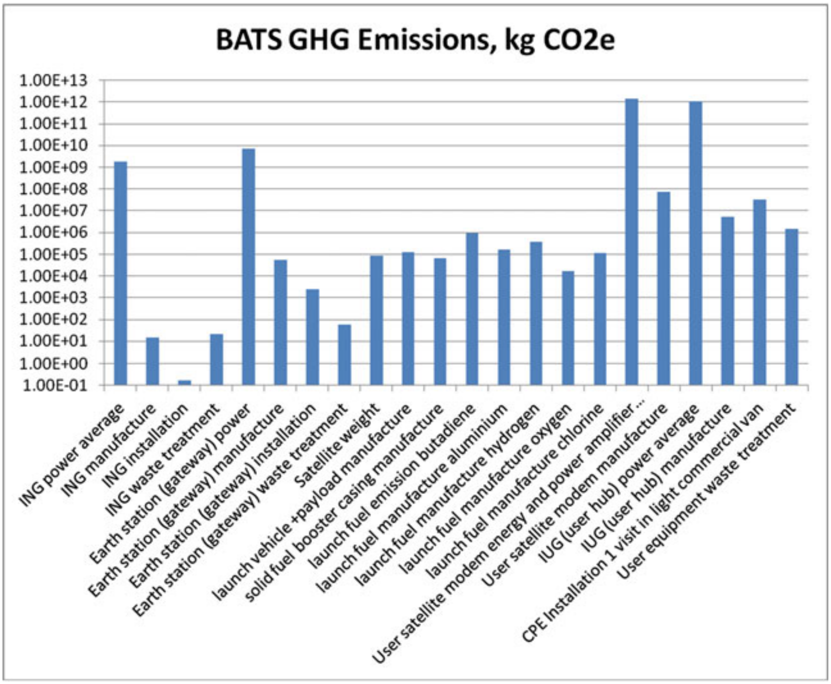

Fig. 8. Emissions of network elements in kg CO_2e

modem (including its power amplifier) and the IUG. The latter two items are the most significant as 6.4 million of these are assumed to be deployed in households in Europe when the service reaches its peak in year 2029. The contribution of all other lifecycle phases including, manufacture, transport, and waste treatment is 116 ktonnes as shown in cell CG42 in Fig. 7. This is only 0.00453 % of the total.

As the most significant contributor, the satellite modem was studied in some detail in an effort to reduce energy usage and emissions. The result presented above is for the case when the satellite modem is operating with a low duty-cycle at a mean power consumption of 7.5 W as compared with an always-on power of 22 W. To make this low duty-cycle possible, traffic is preferentially routed via the ADSL network.

Further modelling work was carried out to compare the hybrid satellite system with terrestrial alternatives: VDSL2, fibre and LTE assuming the same market share number (i.e. number of households) in Europe. A key assumption for the LTE example was the fan-out of the LTE base station which was assumed to be 100 fixed users per base station serving a rural area. This is lower than the average for mobile base stations which is typically 1500. The results of this analysis are shown in Fig. 9.

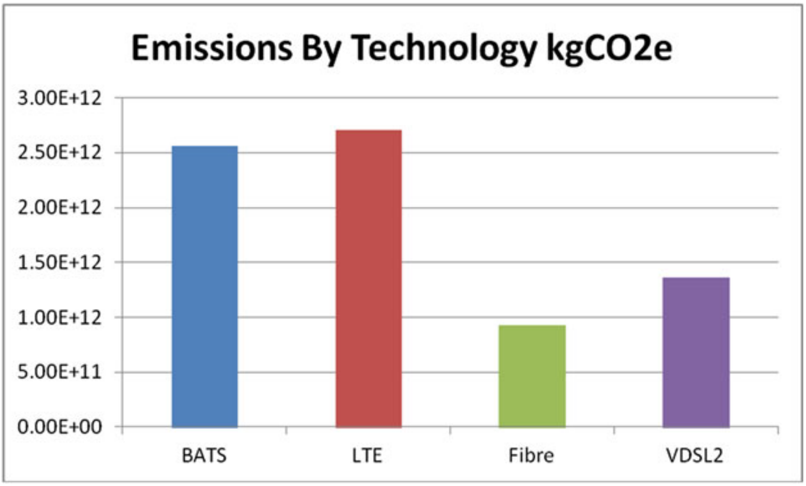

Fig. 9. Comparison of the emissions of four fixed access systems serving rural communities with a downstream rate of approximately 30 Mbit/s

This figure shows that the GHG emissions of the hybrid terrestrial/satellite system (BATS) compares favourably with a terrestrial wireless system based upon LTE technology but the VDSL2 and fibre systems have significantly lower emissions. Note that the hybrid system included operation with a representative low duty-cycle modes which reduced the average power of the modem from 22 W fully-on to 7.5 W average. However, the systems cannot be judged on GHG emissions alone. The hybrid satellite system may turn out to be more economical than the alternatives in rural areas.

8 Conclusion

This paper has shown that, the CO_2e emissions arising from the BATS hybrid terrestrial/satellite system over the lifecycle is 2.56 Gtonnes. This is to a peak market of 6.4 million rural households in year 2029. The lifecycle analysis showed that the electricity used by the customer premises equipment was responsible for the majority of the GHG emissions, assuming that the power plants continue to use fossil fuels. Emissions from manufacture, transport and waste treatment represented only 0.00453 % of the total emissions. Under a 1 % cut-off rule only the in-use emissions from on grid electricity would need to be considered. Manufacture, transport, and waste treatment can be safely ignored. This includes emissions from the manufacture of the satellite launch vehicle and the transport of the satellite into geostationary orbit.

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Acronyms

ADSL	Asymmetric Digital Subscriber Line
BATS	Broadband Access via Integrated Terrestrial and Satellite Systems
CO_2e	Carbon Dioxide equivalent
CPE	Customer Premises Equipment
DEFRA	UK Department for Environment, Food and Rural Affairs
ETSI	European Telecommunications Standards Institute
EU	European Union
FP7	EU 7th R&D Framework Programme
GEO	Geostationary (Satellite)
GHG	Greenhouse Gas
HPA	High Power Amplifier
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communications Technologies
ING	Intelligent Network Gateway
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
ITU	International Telecommunications Union
IUG	Intelligent User Gateway
LAN	Local Area Network
LCA	Life Cycle Assessment
RES	Renewable Energy Sources
UPS	Uninterruptible Power Supply
VSAT	Very Small Aperture Terminal
WEEE	Waste Electrical and Electronic Equipment

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