Role of losses in design of LV distribution circuits for CO_2 emission minimization

Pierluigi Mancarella, *Member, IEEE*, Chin Kim Gan, *Student Member, IEEE*, and Goran Strbac, *Member, IEEE*

Abstract **– This paper discusses the role of losses in distribution circuit design with the aim of minimizing the circuit CO_2 emission impact within a life cycle assessment framework. In order to do so, an optimization problem is formulated in terms of trade-off between emissions embodied in the circuit material and emissions related to power losses occurring over the network operational life. Hence, the role of losses from the environmental outlook is clearly pointed out by solving the optimization problem in closed form. Key outputs of the model are the environmentally optimal circuit capacity for given load patterns and emission parameter inputs as well as the relevant optimal utilization. In particular, the latter provides straightforward indications on the "distance" between the proposed optimal environmental design and a classical peak current based design taken as reference. The results show that optimal environmental utilizations are likely to be extremely low (below 20%) for typical LV distribution circuits, owing to the paramount role of losses. The model proposed enables distribution network operators and policy makers to gain meaningful insights on the parameters affecting the design of distribution networks in the outlook of minimizing their environmental footprint.**

Index Terms **— CO_2 emissions, distribution losses, distribution networks, embodied emissions, environmental impact, life cycle assessment (LCA), optimal circuit design.**

NOMENCLATURE

List of acronyms

ABC	Aerial Bundle Conductor
DNO	Distribution Network Operator
LCA	Life Cycle Assessment
LF	Load Factor
UGC	Underground Cables
OHL	Overhead Lines

List of symbols

a, b, α, β	coefficients used in correlation analyses
A	conductor cross-section area [mm^2]
I	average hourly current circulating in a given circuit [A]
$\hat{I}$	circuit annual hourly maximum current [A]
I_c	circuit current capacity [A]
$\bar{I}_c$	circuit environmental optimal current capacity [A]
L	length of a considered circuit [km]
t	considered hour [h]
T	circuit technical or economic useful lifespan [years]
$\bar{u}$	circuit environmental optimal utilization [%]
ε_{CO_2}	embodied CO_2 emissions per circuit length [kg/km]
λ_{CO_2}	loss-related circuit specific emissions [kg/km/h]
μ_{CO_2}	emission factor [kg/kWh]
ρ	conductor resistivity [$(k\Omega \cdot mm^2)/km$]

I. INTRODUCTION

A major amount of losses occurs at the lower voltage levels, in particular in LV networks. However, the need for decreasing upfront investment costs and maximizing the profits on a short run often drive distribution network operators (DNOs) towards designing and operating networks according to minimum requirements. In particular, this can result in design or replacement policies tending to install minimum circuit capacities that can carry the expected loads, neglecting the influence of energy losses in the longer run. Previous works [1] point out that such an approach is unsuitable for optimal economic design. In fact, in most cases the optimal economic capacity for distribution circuits over the asset life span can be of the order of even five to ten times greater than needed on a simple maximum peak basis. This is primarily a consequence of the continuous operational costs associated to losses.

Apart from the long-term economic impact of losses, today's environmental concerns call for adequately revisiting classical approaches in various fields of power system design and operation. In particular, in the context of the efforts from several countries to reduce their environmental burden and meet their stringent obligations for CO_2 reductions (see for instance UK, [2]), it becomes crucial to understand the role played by losses in circuit design from an *environmental* point of view. In the UK, the criticality of this issue is even exacerbated by the fact that a large part of the distribution network will soon need to be replaced [2]. Neglecting the prominent role of losses in both economic and environmental analyses might lead to inappropriate design and installation of an inefficient network that might stay in operation for decades, or, even worse, that might need to be soon updated again according to new requirements.

On these premises, this paper discusses the role of losses in the design of LV distribution circuits for CO_2 emission minimization. In order to do so, the formulation of an *optimal environmental design problem* is presented. The formulation is based upon balancing the CO_2 emissions embodied in distribution circuits [3] (underground cables, UGC, and overhead lines, OHL) against the emissions associated with electrical losses over the network operational life. In fact, it is intuitive that larger conductor sizes will bring lower energy losses (and then associated emissions) due to lower resistance. However, this would occur at the cost of higher embodied

---

The authors are with the Department of Electrical and Electronic Engineering, Imperial College London, Exhibition Road, SW7 2AZ, London, UK (e-mail: {p.mancarella,ckgan06,g.strbac}@imperial.ac.uk).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

emissions, roughly proportional to the amount of circuit material, so that an optimal trade-off can be sought within a Life Cycle Assessment (LCA) [3,4] framework. Embodied emissions are estimated on the basis of available emission inventories [5] and network equipment catalogues, from which suitable correlations to be used in methodology proposed are drawn. On the other hand, an emission factor approach [6] is adopted to assess the emissions associated with distribution power losses over the circuit lifetime.

The optimization problem is solved in closed form, which leads to the definition of an *optimal environmental capacity* once given the load pattern profiles and the needed environmental inputs. In this way, the factors affecting the optimal design can be clearly highlighted, enabling to get insightful indications on possible actions to carry out in order to improve the environmental performance of the network asset. In addition, the relevant impact of changes in the input parameters can be easily addressed. The specific focus of the paper is set on identifying the circuit *optimal environmental utilization* for different load patterns and circuit types, allowing, in particular, straightforward comparison with a peak current-based design strategy.

Case study applications relevant to UGC and OHL typically used in the UK illustrate some numerical aspects of the environmental design proposed, pointing out, in particular, the role of losses in the presence of different load and emission configurations. In addition, given the uncertainty of the available data (especially with reference to embodied emissions) and the range of possible applications in different countries, sensitivity analyses are carried out in order to evaluate the robustness of the results. A practical application to a rural network also shows the impact of the optimal environmental design in terms of circuit selection.

II. OPTIMAL ENVIRONMENTAL DESIGN OF DISTRIBUTION CIRCUITS

A. Embodied Emissions

The production of every product requires a certain amount of energy. Relevant emissions (of CO_2, in particular) are associated to such energy. Hence, it is possible to define the concept of *embodied emissions* in terms of the emission amount associated to the specific product over pre-defined lifetime LCA boundaries [3-5,7], including upstream and downstream components such as extraction of the raw material and final disposal of the waste, respectively. However, establishing suitable boundaries is often arguable (for instance, if some disposed material can be recycled), so that the data that can found in inventories are typically characterized by large uncertainty.

In order to estimate the embodied emissions for different distribution circuits, commercial catalogues have been used to define the geometric and electrical characteristics of different UGC/OHL types and capacities available in the market. On the basis of these data, the emissions embodied in each circuit type (materials for conductor, insulation, bedding, etc.) have been estimated from available inventories [5]. From the analyses in [3], other embodied emission components such as maintenance or installation are reported to be of minor impact. In addition, as in this work like-for-like typologies are analysed (namely, either UGC, mostly used for urban areas, or OHL, mostly used for rural areas), maintenance and installations components do not differ significantly within the range of capacities considered [3], and can thus be neglected in a comparative assessment with very good approximation.

From the equipment data, a correlation analysis has been carried out in order to formulate generic laws to be used in the analysis. In particular, *power-type* correlations have been found to fit very well the data for a range of available UGC and OHL, yielding

$$I_c = a \cdot A^b \tag{1}$$

relating the rated current-carrying capacity I_c [A] to the cross-section area A [mm^2], and

$$\varepsilon_{CO_2} = \alpha \cdot I_c^{\ \beta} \tag{2}$$

relating the embodied content of CO_2 emissions per circuit length ε_{CO_2} [kg/km] to the current-carrying capacity I_c. The entries a, b, α, and β in (1) and (2) are the correlation coefficients found through a standard least-square estimation technique.

B. Emission Factor Model for Energy Losses

In order to characterize the CO_2 emissions associated to power system operation, it is possible to put forward an energy output-related emission factor model [6]. More specifically, the CO_2 mass emitted while producing electrical energy is expressed through the relevant *emission factor* μ_{CO_2}, *i.e.*, *specific emissions* per unit of output [kg/kWh]). The numerical value of such emission factor depends on the hourly generation characteristics of the specific power plants, the dispatching order, and so on. Possibly, the evaluation of emission factors should also be carried out on the basis of an LCA approach [7].

Energy losses occurring in electrical distribution circuits can thus being associated to additional CO_2 emissions through the emission factor value from the bulk electricity production. In particular, focusing on a three-phase circuit, it is possible to express the emissions λ_{CO_2} relevant to distribution losses per unit of length and per hour [kg/km/h] as

$$\lambda_{CO_2} = 3 \cdot \mu_{CO_2} \cdot {}^{\rho}\!/_{A} \cdot I^2(t) \tag{3}$$

where ρ is the average conductor resistivity [(kΩ·mm^2)/km], and $I(t)$ is the phase average current [A] circulating in the circuit at hour t.

C. Formulation of the Optimization Problem

The objective of this work is to find the optimal environmental design (that is, optimal circuit capacity so as to minimize the overall life cycle CO_2 emissions) for given LV distribution circuit typologies and load configurations. In particular, this approach enables to highlight the potential role of losses for different load and environmental configurations. For this purpose, we assume that CO_2 emission effects are deemed equivalently if occurring now or in the future[1] over the network technical or economic useful lifespan T [years]. In addition, let us assume that a same hourly load pattern, expressed through the current $I(t)$ in (3), occurs over each year. In this case, the objective function to minimize can be written as

$$\min_{I_c}\left(\frac{\varepsilon_{CO_2}\cdot L}{T}+L\cdot\sum_{t=1}^{8760}\lambda_{CO_2}(t)\right) \tag{4}$$

In (4), the first term represents the *equivalent annual emission content* [kg] *embodied* in a certain circuit of length L [km] (including all the phase, neutral and earth conductors, in case, as well as insulation, bedding, protective sheath, and so on); the second term represents the annual emission content [kg] associated with energy *losses* occurring during the circuit operation.

D. Optimal Environmental Capacity

After substituting (1) in (3), and highlighting the role of I_c, the optimization problem (4) can be solved analytically by posing

$$\frac{\partial}{\partial I_c}\left(\frac{\alpha\cdot I_c^{\beta}\cdot L}{T}+\frac{3\cdot\rho\cdot L}{\left(I_c/a\right)^{\frac{1}{b}}}\sum_{t=1}^{8760}\mu_{CO_2}(t)\cdot I^2(t)\right)=0 \tag{5}$$

which leads to a closed formula for the *environmental optimal current capacity* $\overline{I}_c$:

$$\overline{I}_c=\sqrt[\beta+1/b]{\frac{3\cdot\rho\cdot\sum_{t=1}^{8760}\mu_{CO_2}(t)\cdot I^2(t)}{\beta\cdot\alpha/T\cdot b\left(1/a\right)^{\frac{1}{b}}}} \tag{6}$$

The expression (6) yields the current capacity that minimizes the life cycle (embodied and loss-related) emissions of a given circuit type carrying the hourly current $I(t)$ over T years. The optimal capacity is independent of the circuit length, and depends on the circuit characteristics (for given families of UGC and OHL, in particular), load patterns and power system emission characteristics.

The relation (6) somehow reflects the rationale itself of the environmental optimization and enables to highlight the role of losses in the optimal design. In fact, the numerator refers to the operational emissions associated with losses, while the denominator refers to the circuit embodied emissions. Hence, an increase in the weight of losses, depending on the conductor resistance, load patterns or emission factors, will result into a higher optimal capacity, since larger conductors will bring about lower losses. On the other hand, if the role of embodied emissions increases (larger denominator), the optimal environmental capacity will be lower, since larger cables bring about larger embodied carbon footprint.

E. Optimal Environmental Utilization

The considerations relevant to the role of losses and their impact on the optimal environmental capacity (6) can be highlighted by introducing the *optimal environmental utilization* of the circuit for given load patterns. More specifically, this optimal utilization $\overline{u}$ is defined as the ratio of the maximum annual current $\hat{I}$ circulating in the circuit to the optimal capacity $\overline{I}_c$ determined from (6):

$$\overline{u}=\frac{\hat{I}}{\overline{I}_c} \tag{7}$$

In this way, the expression (7) allows a straightforward comparative assessment between the optimal environmental design proposed here and the peak current design taken as a reference benchmark. In particular, lower values of $\overline{u}$ indicate higher weight of losses in the emission minimization. At the same time, the utilization values can be used as a useful metric to indicate the "distance" between the environmental design proposed and a (theoretical) peak load design approach, for which the utilization would be ideally equal to 100%.

III. CASE STUDY APPLICATIONS

A. Emissions Embodied in LV Cables and Overhead Lines

In order to illustrate some numerical instances of the methodology proposed, correlation analyses have been run to characterize the embodied emissions in typical LV UGC and OHL used by DNOs in the UK, according to the procedure illustrated in Section II.A:

- For UGC, typical "Wavecon" cables have been analysed; these cables are composed of aluminium phase conductors and a copper conductor with function of combined neutral-earth circuit, insulated in XLPE.
- For OHL, Aerial Bundle Conductor (ABC) types, with aluminium phase and neutral conductors, again insulated in XLPE, have been selected for the analysis.

The results from the correlation studies run are shown in Fig. 1 (for UGC) and Fig. 2 (for OHL) with reference to the relation (1), and in Fig. 3 (for UGC) and Fig. 4 (for OHL) with reference to the relation (2).

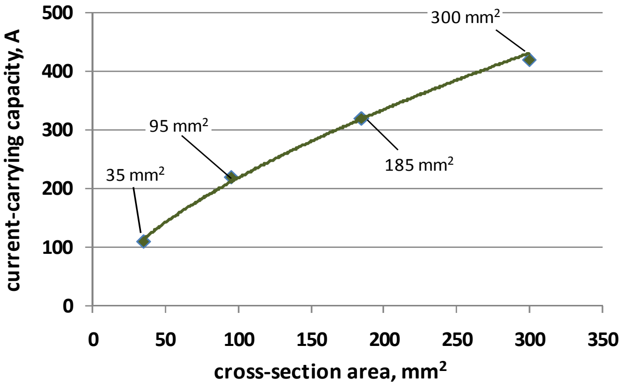

Fig. 1. Current-carrying capacity vs. cross-section area for LV UGC.

---

[1] Carbon dioxide effects are generally assessed on the basis of a 100-year permanence time in the atmosphere [7]

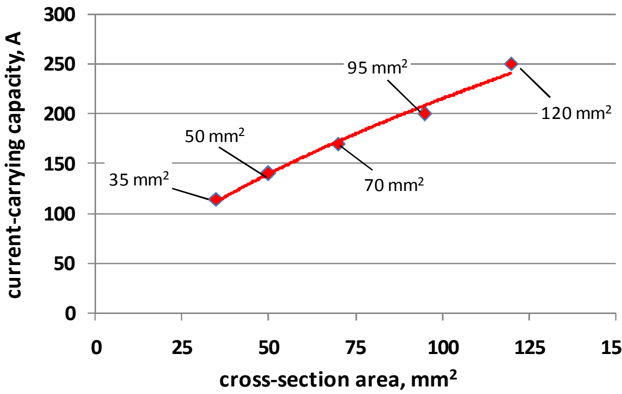

Fig. 2. Current-carrying capacity vs. cross-section area for LV OHL.

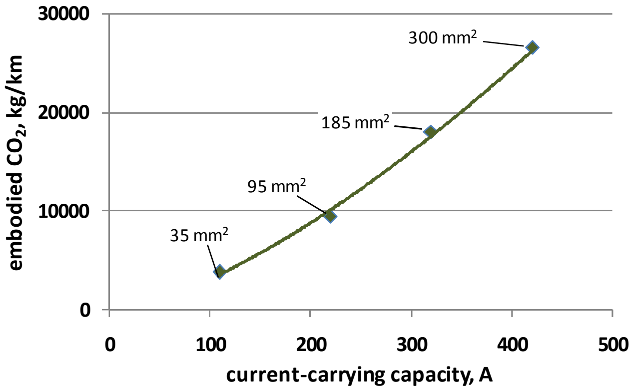

Fig. 3. CO_2 embodied emissions vs. current-carrying capacity for LV UGC.

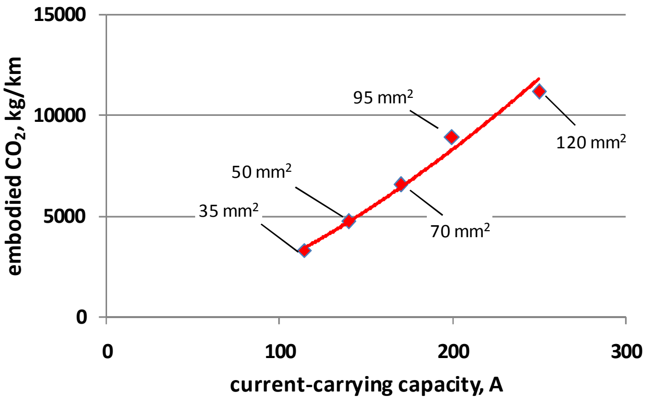

Fig. 4. CO_2 embodied emissions vs. current-carrying capacity for LV OHL.

The typical correlation trends shown in these pictures are a straight consequence of the physical mechanisms governing losses generation (which is related to the amount of material and then to the volume) and cooling (depending on the surface area) in electrical circuits. Such correlations are generally nonlinear and lead to general nonlinear functions for the expressions (6) and (7), as exemplified below.

B. Optimal Utilizations for Cables and Overhead Lines

In order to assess the impact of losses within the optimal environmental design proposed, the optimal utilization (6) has been calculated for various peak currents and for different load patterns, characterized by different loading level durations and thus by different load factors. More specifically, three set of load patterns have been considered, namely:

1. *Set 1*: current equal to peak values for 8760 hours (100%) per year, with load factor $LF = 1$;
2. *Set 2*: current equal to peak values for 4380 hours (50%) per year and equal to zero for the rest (50 %) of year, with $LF = 0.5$;
3. *Set 3*: current equal to peak values for 2190 hours (25%) per year, equal to half of the peak load for 4380 hours (50 %) per year, and equal to zero for the rest (25%) of year, with $LF = 0.5$.

The circuit-related parameters to be used as input in (6) have been drawn from the correlation analyses illustrated in Fig. 1 to Fig. 4; in addition, the UK average emission factor (μ_{CO_2} = 0.430 kg/kWh [8]) has been used, assuming 30 years of technical life. The relevant results are reported in Fig. 5.

The trends shown in Fig. 5 for the optimal utilization with respect to peak currents can be explained by inspection of the expressions (6) and (7), from which it is possible to work out that

$$\bar{I}_c \propto \hat{I}^{\frac{2}{\beta+1/b}} \quad \Rightarrow \quad \bar{u} \propto \hat{I}^{\frac{\beta+1/b-2}{\beta+1/b}} \qquad (8)$$

Typical numerical values found for the root exponent $\beta + 1/b$ in (6) are around 3 for both UGC and OHL, so that from (8) the characteristic shape of the optimal utilization $\bar{u}$ relative to the peak current $\hat{I}$ in Fig. 5 can be derived.

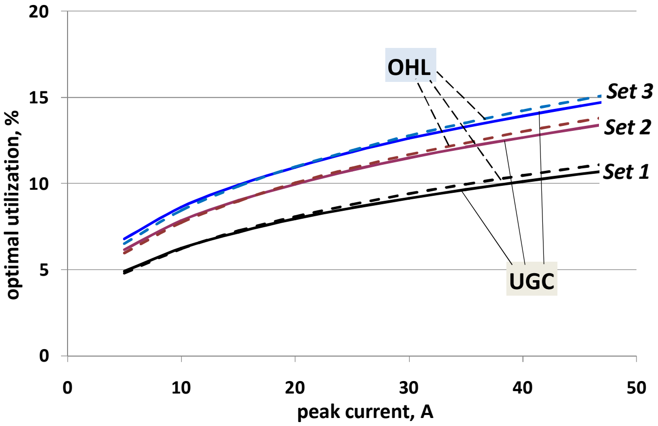

Fig. 5. Optimal environmental utilization of LV UGC and OHL for different peak currents and load patterns.

If the circuit design were driven by using a minimum investment cost method, the major constraint would be not to overheat the conductor dangerously, and theoretical value of utilization would be equal to 100%. Practical finite availability of circuit ratings would lead to pick up available capacity values immediately above the peak current. Under an optimal environmental design strategy, instead, which explicitly takes into account losses, it can be appreciated in Fig. 5 how utilization values are much lower. In other words, the optimal environmental capacity is much higher than the maximum annual current. In particular, for the considered interval of peak currents (5÷50 A), utilization values range between about 5% and 15%, increase with the peak current, and decrease with increasing load factor. Indeed, for the maximum *LF* (equal to 1 in *Set 1*, with the same peak current throughout the year) the weight of losses is foremost significant, so that the minimization process yields a large optimal current capacity. While the *LF* decreases in *Set 2* and *Set 3*, the impact of losses decreases, and so does the optimal capacity, which leads to higher utilization figures. In addition, even with the same *LF* = 0.5, *Set 3* exhibits peak duration lower than *Set 2*, which corresponds to lower losses and thus higher optimal utilization. Looking at OHL and UGC, for a same value of peak current and same set of load pattern, the optimal utilization for UGC is slightly lower than for OHL. However, the results in Fig. 5 are meant to be for illustrative purposes and to point out typical trends. If willing to carry out a comparison between UGC and OHL, more detailed analyses should be run (see for instance [3]), which is outside the scope of this work.

C. Sensitivity to Lifetime and Embodied Emissions

In order to test the robustness of the results found and the role of specific parameters involved in the model proposed, sensitivity analyses have been run to study the dependence of the optimal utilization (6) on the embodied emission content ε_{CO_2} and on the circuit lifetime T. Fig. 6 shows the results of these analyses for OHL and with the circuit current assumed constant throughout the reference year (corresponding to *Set 1* defined in Section III.B) and equal to $I = 50$ A.

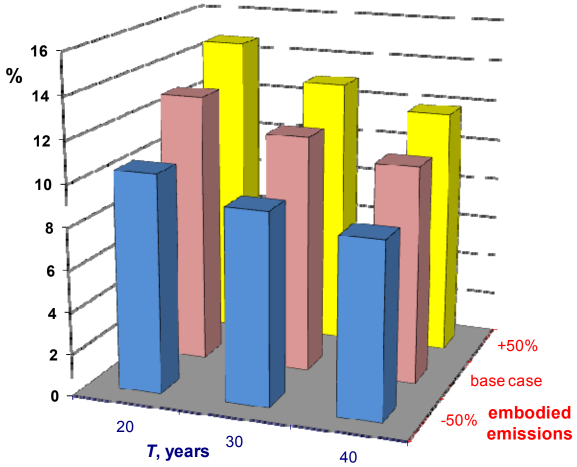

Fig. 6. Optimal environmental utilization: sensitivity to lifetime and embodied emissions for typical LV OHL, with $I = 50$ A.

From the results, it can be appreciated how optimal utilization values are relatively robust even with respect to large variations of the considered parameters. Focusing for instance on the case with $T = 30$ years, the optimal utilization passes from 11.5% to 9.5% and 13% if ε_{CO_2} decreases or increases by 50%, respectively. The optimal utilization figures are also relatively stable with respect to large variations in the circuit lifetime. For instance, for base embodied emissions the optimal utilization varies from 10.5% to 13% passing from 20 years to 40 years of lifetime. Hence, the relatively low optimal utilization values found in the study represent typical characteristics of the LV circuits analysed, as a consequence of their physical properties and of the power system emission factor values considered in the analysis.

D. Sensitivity to Emission Factor and Embodied Emissions

Different countries exhibit a wide range of emission factor values characteristic of the average environmental performance of the bulk power system. In addition, although the analyses carry out here have referred to an average UK value, hourly, daily and seasonal changes in the actual overall emission factor do occur, due to different power plant dispatching. As a further point, on an average basis the bulk emission factor might change over the years due to power system, evolution. Hence, useful indications on the robustness of the results found in the light of evolving situations and of different applications in different countries can be given by running sensitivity analyses with respect to the average emission factor used as input in (6). In this respect, Fig. 7 shows the changes in $\bar{u}$ in OHL for different values of μ_{CO_2} and for the three embodied emission cases already analysed. Again, $I = 50$ A throughout the reference year, with $T = 30$ years.

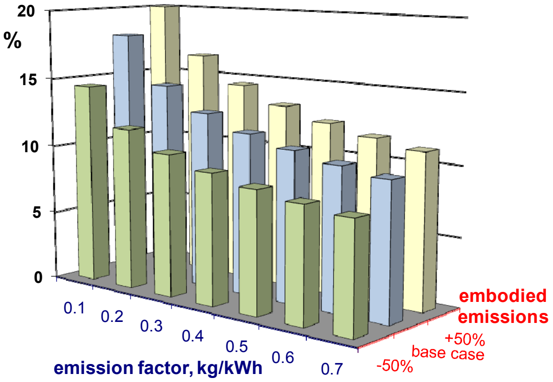

Fig. 7. Optimal environmental utilization: sensitivity to emission factor and embodied emission variations for typical LV OHL, with $I = 50$ A.

The results in Fig. 7 show that the optimal utilization increases with decreasing emission factors, as expected from (6). Indeed, for lower grid carbon emissions the role of losses is less important. It can also be noticed how for relatively high emission factor values the optimal utilization does not change significantly. For instance, this can be appreciated for utilizations calculated with emission factors in the range 0.5÷0.7 kg/kWh (typical of countries dominated by fossil-based power plants), while the increasing trend is more visible for the lower emission factor figures (0.1÷0.3 kg/kWh, typical of countries with large shares of renewable and/or nuclear sources). This is again due to the fact that the role of losses becomes less significant due to lower associated emissions. The optimal utilization sensitivity to emission factor variations also slightly increases with increasing embodied emissions, as losses affect more the circuit design.

E. Optimal Utilization for a Typical LV Rural Network

The design approach proposed has been applied to a typical UK rural network to identify the characteristics of the optimal environmental network with respect to a minimum investment network. The typical network selected has radial topology, is composed of 2000 customers characterized by typical residential load patterns with a load density of 0.29 MVA/km^2, and has a total length of about 30 km. For such a network, Fig. 8 shows the length of the different three-phase ABC circuit types in the case of optimal environmental design for a network life of 30 years. For the sake of comparison, the same network designed on the basis of peak current would be all composed of 35-mm^2 conductors. However, it must be underlined that this comparison is only for indicative purposes, since further constraints such as voltage drops, fault levels, reliability and security requirements, and so on, would lead to increase the minimum capacity found following a minimum investment cost strategy. In any case, it is clear how the optimal environmental design would lead towards installation of much larger conductors, owing to the role of losses and of the associated emissions. This is confirmed by Fig. 9, plotting the frequency histogram of the environmental optimal utilization in all the network circuits for different bins. The optimal utilization values tend to cluster towards the smaller figures due to the predominant role of losses. These results are in general agreement with the findings in [3].

The annual emission balances (embodied emissions referred to an equivalent year and loss-related emissions) for the two design strategies are reported in Table I. The results highlight how although the optimal environmental design is characterized by a higher equivalent annual amount of embodied emissions, it allows a dramatic saving in terms of loss-related emissions relative to the peak design strategy. In this case, considering the overall network life of 30 years, the environmental design proposed would lead to an LCA emission reduction of about 572 tons of CO_2.

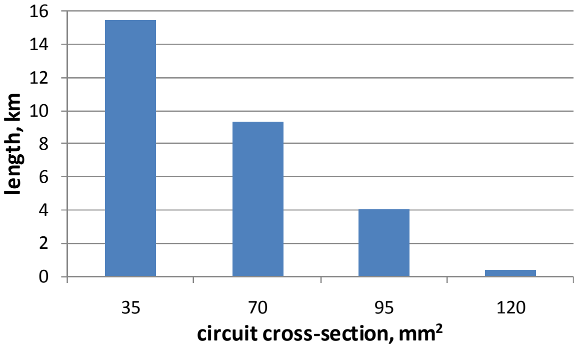

Fig. 8. Lengths of different circuit types in the typical LV rural network analysed, designed according to the optimal environmental approach.

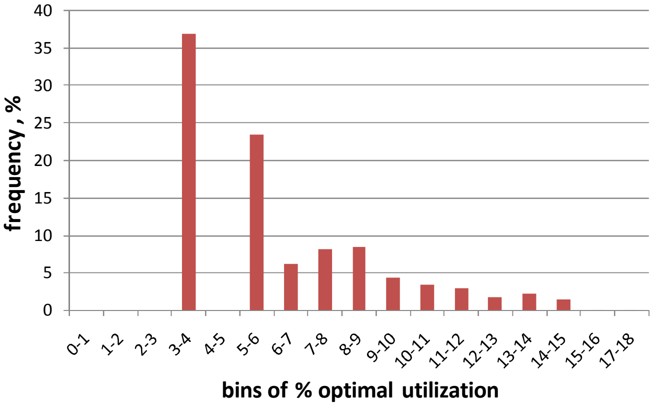

Fig. 9. Frequency histogram of the optimal environmental utilization (in %) in the LV rural network analysed.

TABLE I
ANNUAL EMISSION BALANCES FOR PEAK AND ENVIRONMENTAL DESIGN STRATEGIES IN THE CONSIDERED LV RURAL NETWORK

Annual emissions	*Peak design*	*Optimal design*
Embodied [kg/year]	3507	5374
Loss-related [kg/year]	28507	7569
Total [kg/year]	32014	12943

IV. CONCLUDING REMARKS AND FUTURE WORKS

This paper has discussed the role of losses in distribution circuits from an environmental standpoint. For this purpose, an optimization problem based on trading off the circuit embodied emissions and the operational loss-related emissions has been formulated and solved in closed form, thus providing clear indications on the factors affecting the optimal design. Results for typical LV UGC and OHL used by UK DNOs have shown that the optimal design of distribution circuits for CO_2 emission minimization is primarily driven by the weight of losses. Optimal utilizations are very low, typically below 20%. Hence, network design policies based on optimizing investment costs by installing circuits with minimum capacity able to carry the estimated loads prove to be inadequate from an environmental outlook. In this respect, the results found back and strengthen classical works that point out the role of losses also from an economic standpoint. In addition, it is worth mentioning that although the circuit design proposed does not take into account network-related requirements such as voltage drops, reliability and security criteria, and so forth, relatively larger circuits are likely to meet network standards without need for further adjustments [1].

Works are in progress to refine the model taking into account a number of issues that have not been addressed here, such as load growth, applications to network design taking into account operational constraints and network topology, and so on. However, the model introduced can already provide important indications on strategic directions that DNOs and policy makers could undertake in order to increase the energy efficiency of distribution networks.

V. REFERENCES

[1] S.Curcic, G.Strbac and X.-P.Zhang, "Effect of losses in design of distribution circuits", *IEE Proc.-Gener. Transm. Distrib.*, Vol. **148**, 2001, pp. 343-349.

[2] House of Commons, "Renewable electricity – generation technology", Fifth Report of Session 2007-2008, Vol. 1, London, UK, June 2008.

[3] C.I.Jones and M.McManus, "Life cycle energy and carbon assessment of 11 kV electricity overhead lines and underground power cables", Report for WPD, SERT, University of Bath, July 2008.

[4] G.P.Hammond and C.I.Jones, "Embodied energy and carbon in construction materials", *Proc. Of the Institution of Civil Engineers – Energy*, **Vol**. 161, 2008, pp. 87-98.

[5] G.P.Hammond and C.I.Jones, "Inventory of carbon & energy (ICE), Version 1.6a", SERT, University of Bath, available from www.bath.ac.uk/mech-eng/sert/embodied/.

[6] G.Chicco, P.Mancarella, R.Napoli, "Emission assessment of distributed generation in urban areas", *Proc. IEEE Power Tech 07*, Lausanne, Switzerland, 1-5 July 2007, pp. 532-537.

[7] D.Weisser, "A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies", *Energy*, Vol. **32**, 2007, pp. 1543-1559.

[8] Carbon Trust, "Micro-CHP Accelerator – Interim report", Carbon Trust, UK, November 2007.