New spatiotemporally resolved LCI applied to photovoltaic electricity

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Abstract We present a new Life Cycle Inventory (LCI) calculation methodology that we call ESPA (Enhanced Structure Path Analysis). The ESPA method is aiming at calculating spatiotemporally defined LCIs while minimizing the difficulties of spatiotemporal information database management. The ESPA methodology uses the Structure Path Analysis capacity to describe completely the supply chain which enables the linkage of temporal distributions defined in the database. An example of electricity production by a multi-crystalline silicon 3 kWp installation is used to describe the ESPA capabilities in details. This new methodology underlines the need for the LCA community to discuss how temporal information should be described in future database. If used to its full potential, the ESPA methodology should enable a significant improvement in the representativeness of LCA results.

1 Introduction

In the past few years, many publications have described the aspects that will need to be considered for improving the representativeness of Life Cycle Assessment (LCA) modelling [1-4]. In this extensive list of aspects, we decided to focus our work to representing spatial and temporal characteristics of scenarios.

It now has been showed that impact factors for certain substances vary quite dramatically if we consider specific site of emissions characteristics [5-7]. In the case of emission in water some impact factors can span a 10 order of magnitude range [7]. This high variability means that taking spatial variability into account can have significant effects on LCA results.

Today, the LCA methodology has poor time-related consideration capacity [1,8]. Most impact factors are evaluated with steady-state models since there is no temporal information available in the Life Cycle Inventory (LCI). Levasseur et al. [8] have shown that a negligence of temporal considerations can lead, for example, to an underestimation of global warming potential assessment.

Those two observations clearly show a need for LCA to consider both spatial and temporal characteristics of assessed scenarios. For now, few researches have been undertaken. Spatially [9] and temporally [8] informed LCI computations have been discussed previously, but there is a need for further investigation.

We think that spatiotemporally defined LCA are necessary but the LCI calculation phase is still a complex issue when considering its implementation. To contribute to its simplification we consider different aspects for the spatiotemporally informed LCI implementation. And so, we propose a new spatiotemporal LCI calculation methodology with the related requirements for the spatiotemporal description of the database. For the sake of clarity we use photovoltaic (PV) electricity production as an example to describe the methodology.

2 Spatiotemporally informed LCI calculation

2.1 Spatially informed LCI calculation

Mutel and al. [9] have proposed a way to consider the spatial variability when making an LCA. We analyze this method to identify if and how we can extrapolate it to a spatiotemporally informed LCI calculation step.

The basic principal of Mutel's method is to use different unit process in the database for technological processes of different sites. Equation 1 describes Mutel's calculation method to evaluate global impacts [9].

$$\mathrm{Imp} = (G \circ E)(I - T)^{-1}P \qquad (1)$$

Where:

Imp is the vector describing the impacts (dimension n)

G is the impact factors matrix (dimension: n × m)

E is the environmental exchange matrix (intervention matrix) (dimension: n × m)

I is the identity matrix (dimension: m × m)

T is the technology matrix (physical or economical flows) (dimension m × m)

P is the process vector (describing the functional unit) (dimension m)

The G and E matrixes are multiplied with the Hadamard product (∘)

The spatial aspect is considered in the calculation since each line of the G, E and T matrix is linked to one site only. The geographical precision varies with the available database information.

2.2 Temporally informed LCI calculation

The same basic principal could be used to consider temporal variation in a scenario's description. This means that different unit process would be defined for every discrete moment a technological process occurs in a supply chain. And so, emission would be distributed over the time range in which the technological process occurs. New temporally dependent impact factors (in matrix G) could then be used to evaluate the global environmental impacts.

2.3 Today's spatiotemporally informed LCI calculation

We acknowledge that Mutel's methodology can be used to compute spatiotemporally resolved LCA. The use of Mutel's methodology has two main advantages. First, it is easy to implement with the computation structure of today's LCA databases and software. Second, it works with any type of spatiotemporal information.

On the other end, we expect that information management difficulties will arise when LCA scenarios' precision and complexity will increase. Two main difficulties with Mutel's methodology can be expected in the future:

1) Reusability of a scenario's description for different LCAs:

A useful reuse of unit processes[1] description at multiple levels of a supply chain will be increasingly rare when the spatiotemporal precision increases. This is based on the observation that a unit process will rarely happen more than once at the same site and time at two different levels of a supply chain. And so, we expect that we would need to redefine the full list of unit processes for each different scenario.

2) Size of the needed database:

The spatialization of a database will increase greatly its size since Mutel's method requires that a different process unit is to be defined for each site. The size of regions (which could correspond to a sub-hydrological region [7]) that might be used to reach representative impact values implies a need to duplicate some industrial process many times in a database. With the available knowledge we

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[1] Unit which divides the database information

have today it is still difficult to evaluate to what level we would need to extend the size of the database.

The same argument applies to the number of processes that will be needed to represent time dependence of scenarios. Two identical industrial processes occurring at two different times require to be defined twice in the database. The number of definition will increase rapidly if the temporal precision is increased to get more realistic results.

3 Development hypothesis

We think that temporal information needs to be standardized and described through a distribution scheme in order to minimize the amount of data needed to describe similar complex scenarios in a database. The idea of describing temporal information with distribution has already been proposed by Levasseur et al. [8] when they described the division of moments of emission with discrete functions.

4 New spatiotemporally informed LCI calculation principle

We propose to use the Structure Path Analysis (SPA) [10-12] inventory calculation methodology to take advantage of the previously mentioned hypothesis. The SPA methodology is interesting since it has the capacity to identify links between the unit processes of a supply chain (scenario). We propose to adopt this calculation methodology to manage spatiotemporal information and enable spatiotemporally informed LCI calculation.

We call the newly proposed spatiotemporally informed LCI calculation methodology: Enhanced Structure Path Analysis (ESPA). With this ESPA method we are able to reuse process unit definition inside the description of a supply chain because temporal information is decoupled from the database structure. The ESPA calculation methodology is simple and only requires a few adjustments on a database information structure.

5 ESPA methodology

We now describe the ESPA calculation methodology, its database structure requirements and the expected results format.

5.1 General Description

Equation 2 presents how to calculate the spatiotemporally informed LCI.

$$INV = [EIP][ETP][ET^2P][ET^3P][\ldots][ET^xP] \qquad (2)$$

Where: INV is the LCI matrix with n substances (extracted or emitted at different sites) and x columns for the x levels of the supply chain (dimension n × x)
E, T and P are the same matrixes and vector as presented in equation 1 and their multiplication defines a column vector
The lines and columns of T and P represent different technological processes at different sites
The columns of matrix E represent the different extractions or emissions from the different technological process at different sites

Each element of the E matrix is linked to a temporal exchange distribution ($f_e(t)$). Moment 0 of those distributions is fixed by moment 0 of the responsible technological process. The elements of the vector defined by IP, TP, T^2P,…, T^xP are linked to a particular site and to a temporal process distribution ($f_p(t)$) just like matrix E elements. Here, the site and temporal functions are defined in technological processes which are previously described on the supply chain.

To obtain the spatiotemporally informed extractions or emissions inside the inventory matrix (INV) we need to make a convolution between the exchange and process temporal distributions ($f_e(t)$ and $f_p(t)$) while multiplying the elements of the E and IP, TP, T^2P, …, T^xP vectors. Full temporal distributions for the extractions or emissions of a substance in one site will be obtained by adding all the temporal distributions of the related line of the INV matrix.

Only relevant processes have to be described in each level of the supply chain. This will probably have implication on the computation time but it still needs to be evaluated through tests.

5.1.1 Spatial information

Spatial information will be linked to a line of vector P for the first level. For the second level, the spatial information will be made available in the description of the P unit process description and structured by the TP vector. The same logic can be applied for higher levels within a supply chain. The precision of spatial information can vary and depends on available information.

The ESPA method uses the same principals as Mutel's method for spatial information propagation in the LCI calculation. This means that this part of the calculation method does not solve the difficulties of Mutel's methodology.

Spatial information cannot be standardized in environmental modelling since there are no simple structures to define spatial links in a supply chain. In other words, a decoupling of spatial information from the database structure would raise important problems with LCA modelling representativeness.

5.1.2 Temporal information

The decoupling of temporal information from a database structure will be useful in decreasing the amount of processes needed to model a complete scenario. The structure we propose should answer both of Mutel's method difficulties at least for the temporal aspect.

Since we use a convolution to propagate temporal information, the temporal precision of the LCI will be equal to the lowest level of precision on the whole calculation propagation. This means that if we want to have more precise LCI results, we need to define temporal information for the database as precisely as possible for all processes.

5.2 Database requirements to use the ESPA method

The ESPA methodology requires a specific description of spatial and temporal information. For now, many available databases (such as ecoinvent[2] or ELCD[3]) are informed on the spatial aspect even if the precision is rather low (usually at country level). On the other hand, the temporal aspect is not informed properly. Only the moment at which the data was assessed is provided. This is not enough, we need information on the duration of the process and on the distributions which inform on when the sub-processes are called or when extractions/emissions occur. Figure 1 presents the list of information that is needed and our proposition for the information structure.

In a unit process definition we first need to define its site and the moment at which its starts (moment t=0). The site will be linked to the site of emission. This is why we need to define processes for each site. Moment 0 will indicate when the product, system or service we are analysing is available. It is not the start of the

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[2] http://www.ecoinvent.org/

[3] http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm

entire life cycle. Duration of the process informs on the possible temporal range of the distributions which are calling other sub-processes or extractions/emissions.

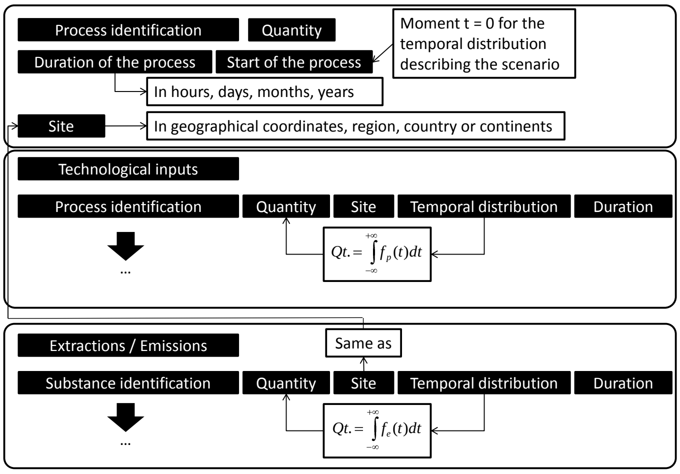


Figure 1: Description of the detailed spatiotemporal information when describing a database unit process

The temporal process distribution ($f_p(t)$) describes at which time and in what amount a sub-process is called. The amount of technological process indicated in the process definition will be the total value over the temporal distribution. Duration will be indicated, for now, to inform on the possible range of the temporal distribution.

The extraction and emission definition for one process will also require a temporal exchange distribution ($f_e(t)$). This is the only new value to be added in the extractions/emissions section compare to a traditional environmental database. The amount of extraction/ emission described in the database defines the total extraction/emission over the entire temporal distribution.

5.3 LCI result structure

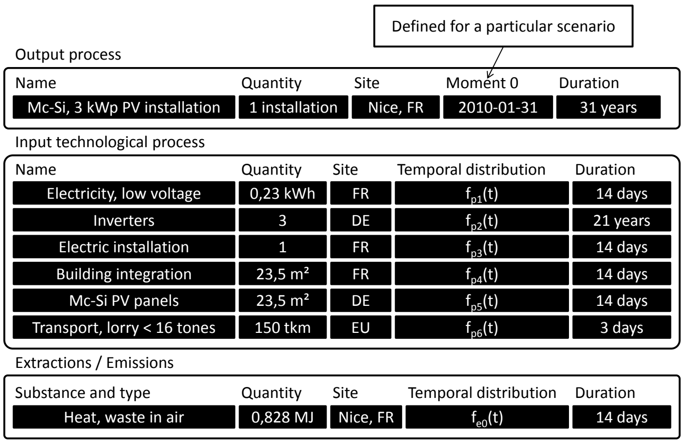
As shown in equation 2, the LCI format is a matrix of dimension n,x. The n lines of the INV matrix represent the sites of extraction or emission of a particular substance. The columns describe the extractions or emissions of level x of the supply chain. Each element of this matrix is linked with a temporal distribution which describes when the extractions or emissions occur. And so, we have all the spatial and temporal information needed to identify where and when an extraction or emission is occurring.

6 PV electricity LCI example

A simplified scenario of PV electricity production will illustrate how and where spatiotemporal information needs to be defined for the LCI calculation steps.

6.1 Database definition (Scenario's description)

The structure proposed in figure 1 is reused here to describe a multi-crystalline silicon 3 kWp PV installation fabrication step. The definition for the unit process which describes the fabrication of a PV installation is shown in figure 2. This information is based on the ecoinvent 2.0 database[4]. Compared to the available information in the ecoinvent database, the new necessary information are the identification of sites, duration and temporal distributions. Site identification could be given by different classification modes (country, region, cities,…) or geographical coordinates. Most of the new information is simple to implement in the database and should only require an extension of attributes. Work wise, the only difficulty will be the definition of the temporal distributions. Tools could be offered to automatically define these distributions from a few critical values just like variability is informed with the shape and variance in ecoinvent.



Output process

Name	Quantity	Site	Moment 0	Duration
Mc-Si, 3 kWp PV installation	1 installation	Nice, FR	2010-01-31	31 years

Input technological process

Name	Quantity	Site	Temporal distribution	Duration
Electricity, low voltage	0,23 kWh	FR	$f_{p1}(t)$	14 days
Inverters	3	DE	$f_{p2}(t)$	21 years
Electric installation	1	FR	$f_{p3}(t)$	14 days
Building integration	23,5 m²	FR	$f_{p4}(t)$	14 days
Mc-Si PV panels	23,5 m²	DE	$f_{p5}(t)$	14 days
Transport, lorry < 16 tones	150 tkm	EU	$f_{p6}(t)$	3 days

Extractions / Emissions

Substance and type	Quantity	Site	Temporal distribution	Duration
Heat, waste in air	0,828 MJ	Nice, FR	$f_{e0}(t)$	14 days

Figure 2: Unit process description of a multi-crystalline (mc-Si) 3 kW$_p$ PV installation and its technological inputs and emission.

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[4] http://www.ecoinvent.org/

6.2 LCI calculation for PV electricity production

Figure 3 indicates how we suggest linking the spatial and temporal information in the ESPA LCI calculation step. The example of Figure 3 is a simplified calculation of LCI since it considers only one type of inventory element (heat waste air emission). We chose this emission since it is found in most of the unit processes of the first levels of the PV electricity supply chain.

The E matrix dimensions will depend on the number of regions that need to be considered for each substance. A product of convolution between distributions is calculated each time two related values are multiplied. When values are added or subtracted the linked distributions are also added or subtracted. For each level, matrix T is defined by the information of vectors P, TP, T^2P,… of the previous level. Vectors P, TP, T^2P,… also define the spatial and temporal ($f_p(t)$) information for vectors TP, T^2P, T^3P,… of the next level.

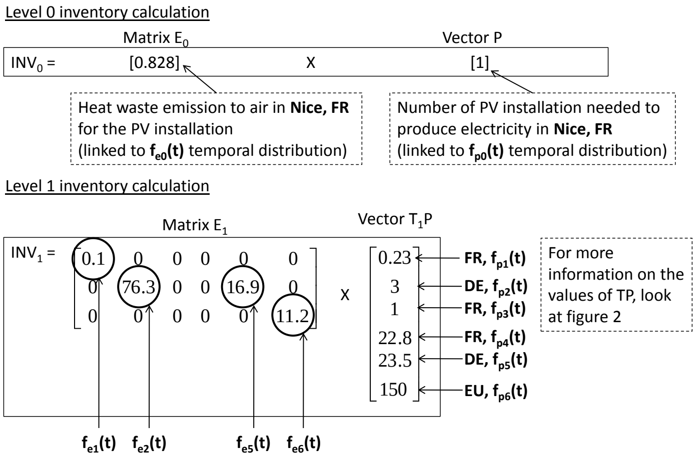

Figure 3: LCI calculation with the ESPA method on the first 2 levels of the supply chain needed for the production of electricity by a PV installation. Values of E matrixes are defined in the ecoinvent 2.0 database.

6.3 Temporal distribution calculation for LCI results

Figure 4 presents the result of one of the product of convolution that needs to be calculated for level 1 of the PV electricity supply chain. The distribution characterising indices are linked to figure 3's information. The dotted rectangle of this example gives the format of the ESPA methodology results.

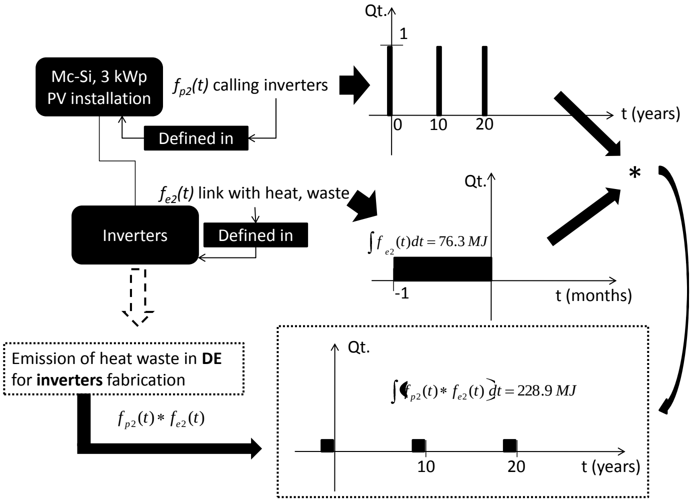

Figure 4: Description of the convolution calculation needed to obtain the emission from the inverters needed for the PV electricity production supply chain

7 Discussion

7.1 ESPA methodology advantages

The ESPA methodology that we propose is the first LCI calculation method that enables the elaboration of a spatiotemporally informed LCI accounting for dedicated spatiotemporal defined databases. Furthermore, this methodology tries to solve future LCI calculation difficulties that might be encountered for a more representative (larger) database.

7.2 ESPA methodology inventory database requirements

If we want to use the ESPA calculation methodology, the current structure of database will need to be partially modified. The most important change will be the addition of temporal description of each sub unit process and extraction/emission calling. We expect that the added work is well worth it since LCA modelling will gain in representativeness. Handling temporal information is a complex issue and we propose to solve this question with an adequate solution. The standard description of temporal information for scenarios should be part of future LCA community discussion to reach common agreement.

The structure in which we define the spatial information of the database is also another requirement of the ESPA methodology. Here, the effort link to this new requirement seems less important since the information is usually already partially available. The most difficult aspect of informing the spatial description of scenario is to evaluate the level of precision that is required to obtain representative results. This level of precision is quite difficult to evaluate without many tests. Those tests will be a big part of the further ESPA methodology developments.

7.3 Further developments

Many tests of the ESPA LCI calculation methodology will be required. They will serve to identify:

- Spatiotemporal modelling difficulties like international transport
- How to present results in a comprehensible manner in order to respect the LCA capacity to serve as a decision tool
- How we should manage the storage aspect on the temporal perspective

A discussion with impact modelling experts will also be needed to link the spatiotemporally defined LCI results with available and new impact analysis methods.

8 Conclusion

We have proposed a new analytical calculation methodology to obtain spatiotemporally defined LCIs that we call the ESPA methodology. The ESPA method takes advantage of the SPA propagation of information capabilities to improve temporal information management.

Database information will need to be improved on the spatiotemporal level in order for the ESPA method to reach full potential. This is an important requirement and the LCA community should discuss how the spatiotemporal information should be implemented in the future.

The PV electricity production example describes only part of the ESPA methodology potential. Further work is needed to enable better representativeness of LCAs that are using a spatiotemporally defined inventory.

9 References

[1] Reap J, Roman F, Duncan S, Bert B; A survey of unresolved problems in life cycle assessment; *International Journal of Life Cycle Assessment*; Vol. 13; 2008; pp. 374-388.

[2] Zamagni A; Buonamici R, Buttol P, Porta PL, Masoni; *Main R&D lines to improve reliability, significance and usability of standardised LCA, Calcas project deliverable D14*; 2009

[3] Finnveden G, Hauschild M, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S; Recent developments in Life Cycle Assessment, *Journal Environmental Management*; Vol. 91; 2009; pp. 1-21.

[4] Guinée J B, Heijungs R, Huppes G, Zamagni A, Masoni P, Buonamici R, Ekvall T, Rydberg T; Life Cycle Assessment: Past, Present, and Future; *Environmental Science & Technology*; Vol.45; 2011; pp.90-96.

[5] Pennington D W, Margni M, Ammann C, Jolliet O; Multimedia fate and human intake modelling: Spatial versus nonspatial insights for chemical emissions in Western Europe; *Environmental Science & Technology*; Vol. 39; 2005; pp.1119-1128.

[6] Potting J, Hauschild M Z; Spatial differentiation in life cycle impact assessment - A decade of method development to increase the environmental realism of LCIA; *International Journal of Life Cycle Assessment*; Vol.11; 2006; pp.11-13.

[7] Manneh R, Margni M, Deschênes L; Spatial Variability of Intake Fractions for Canadian Emission Scenarios: A Comparison between Three Resolution Scales; *Environmental Science & Technology*; Vol. 44; 2010; pp. 4217-4224.

[8] Levasseur A, Lesage P; Margni M, Deschênes L, Samson R; Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments; Environmental Science & Technology; Vol.44; 2010; pp. 3169-3174.

[9] Mutel C L, Hellweg S; Regionalized Life Cycle Assessment: Computational Methodology and Application to Inventory Databases; *Environmental Science & Technology*; Vol.43; 2009; pp.5797-5803.

[10] Defourny J, Thorbecke E; Structural Path Analysis and Multiplier Decomposition within a Social Accounting Matrix Framework; *Economic Journal*, Vol.94; 1984; 111-136.

[11] Lenzen M; Structural path analysis of ecosystem networks; *Ecological Modelling*; Vol. 200; 2007; pp.334-342.

[12] Suh S W, Heijungs R; Power series expansion and structural analysis for life cycle assessment; *International Journal of Life Cycle Assessment*; Vol.12; 2007; pp. 381-390.