Is wood pellet-based electricity less carbon-intensive than coal-based electricity? It depends on perspectives, baselines, feedstocks, and forest management practices

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Abstract
Some studies suggest that the carbon intensity of electricity generated in the United Kingdom by using imported wood pellets from the southern United States is higher than that of coal-based electricity, whereas other studies suggest that the use of wood pellet-based electricity reduces carbon emissions significantly, relative to coal-based electricity. We developed the Forest Bioenergy Carbon Accounting Model (ForBioCAM 1.0) to analyze factors that influence the carbon intensity of wood pellet-based electricity, using a common set of assumptions and the same system boundary. We show that widely differing assessments of the carbon intensity of wood pellet-based electricity depend on the choice of forest management perspectives (landscape or stand), baselines (no harvest, or harvesting for the manufacture of traditional finished wood products), feedstocks (whole trees, pulpwood, or logging residues), forest management practices (change in rotation age), and the duration of the analysis itself. Unlike with a stand perspective, we demonstrate conditions under which a landscape perspective results in carbon savings net of avoided emissions from coal-based electricity. Our results also suggest that the two perspectives of forest management converge in their assessment of the positive carbon effects of various feedstock types used to manufacture wood pellets relative to a no-harvest baseline, and that the use of whole trees for wood pellets results in net carbon savings after a break-even period of about three years relative to a no-harvest scenario. The results of this study can guide future policy deliberations on the use of wood pellets as a renewable energy source worldwide.

Introduction
European power utilities are using imported industrial wood pellets from the southern United States for electricity generation instead of coal, in order to meet national carbon reduction targets by 2020. The European Union (EU), including the United Kingdom (UK), imported about five million metric tons of industrial wood pellets (Forisk Consulting 2018) from the southern United States in 2017, and according to current projections, the export of industrial wood pellets from the southern United States to the EU will reach about six million metric tons by 2020 (Forisk Consulting 2018). The total consumption of wood pellets in the EU in 2015 was 20.3 million metric tons, of which 7.3 million metric tons (about 36%) were used for power generation and the rest to meet heating demand (European Biomass Association (AEBIOM) 2016). Therefore, wood pellets imported from the United States currently comprise about 70% of all wood pellets consumed in the EU, including the UK, for electricity generation.

The carbon savings from the growing use of wood pellets produced in the southern United States for electricity generation in Europe is contentious (Cornwall 2017). This issue has gained more attention as the former Administrator of the United States Environmental Protection Agency recently announced that biogenic carbon emission resulting from the combustion of biomass obtained from managed forests at stationary sources for bioenergy production would be considered as...
carbon neutral (USEPA 2018). At the other extreme, environmental groups (NRDC 2011) and other studies (Moomaw 2017, Schlesinger 2018) have contended that biogenic emissions from wood-based electricity are greater than those from equivalent coal-based electricity, particularly when whole trees are used for the manufacturing of wood pellets to be exported. Our understanding about the carbon benefits related to the use of imported industrial wood pellets for electricity generation relative to coal-based electricity becomes even more challenging, as some studies (Mitchell et al 2012, Jonker et al 2014, Ter-Mikaelian et al 2015, Sterman et al 2018) suggest that any carbon benefit from the use of wood pellet-based electricity is derived only after a few years, as it takes time to pay back the carbon debt created by the release of biogenic carbon at the time of combustion of the wood pellets. This is at least in part because the carbon accounting in these studies starts at the onset of harvest, typically stops after one rotation cycle, and mostly takes a stand-level perspective of forest management. Other studies suggest that the use of wood-based electricity saves at least 60% of carbon emissions relative to coal-based electricity, and that these savings are immediate (Dwivedi and Khanna 2014a, Dwivedi et al 2014b). These studies take a landscape-level approach, where forestlands are maintained for a continuous supply of biomass to a pellet mill.

It is essential to clarify the effect of assumptions on the carbon intensity of electricity generated from wood pellets using a common set of assumptions and the same system boundary. This understanding would help in bringing bioenergy stakeholder groups together for a constructive discussion on the use of wood pellets for electricity generation worldwide, and in the EU in particular. This is especially timely, as the European Parliament and the European Council recently agreed on a revised Renewable Energy Directive that sets a new renewable energy target, where renewable energy will constitute at least 32% of the EU’s gross final energy consumption in 2030 (European Council 2018). A clearer understanding of the carbon benefits of electricity derived from wood pellets imported into the EU will better inform policy decisions related to the use of industrial wood pellets in the renewable portfolio of the EU. Additionally, this understanding will potentially promote investment in Asian countries (e.g. Japan and South Korea) which are in the initial stages of decision-making about the use of industrial wood pellets to generate electricity to reduce carbon emissions and ensure public safety.

In this context, we demonstrate the effects of forest management perspectives, baselines, feedstocks, and forest management practices on the carbon benefits of the transatlantic wood pellet trade for reconciling the differences across existing studies (Khanna et al 2017). In this study, we have covered all the potential scenarios related to the current debate on the carbon intensity of the transatlantic wood pellet trade, to the best of our understanding. Additionally, we have developed a framework that allows for a transparent comparison of the effects of these choices, using a similar set of assumptions within a common system boundary. Furthermore, we have provided a downloadable (available online) Microsoft® Excel-based Forest Bioenergy Carbon Model (ForBioCAM 1.0) for assessing the carbon dynamics of the transatlantic wood pellet trade under a multitude of alternative scenarios.

We show that from a stand perspective, the use of wood pellets for electricity generation results in a carbon debt following the harvest of the stand, as the amount of biogenic emissions are about three percent higher than carbon savings realized from displacing coal-based electricity. On the other hand, from a landscape perspective of forest management, the biogenic carbon emissions from using one stand for electricity generation at a given time are offset in part by simultaneous carbon sequestration on other stands, resulting in no net biogenic carbon emissions due to the burning of wood pellets at the time of electricity generation. As a result, the carbon saving related to the use of wood pellet-based electricity is higher than that of coal-based electricity. Additionally, we demonstrate that the carbon intensity of electricity generated in the UK from imported wood pellets depends on the type of feedstock used to manufacture wood pellets to be exported, as the availability of potential feedstocks varies over time. Furthermore, we demonstrate that the types of baseline (use of roundwood products for traditional products or no harvest) used to measure net carbon sequestered in the system could significantly affect the net carbon balance related to the use of wood pellets for electricity generation. Finally, we show that the carbon intensity of generated electricity will vary with changes in forest management practices (e.g. rotation age), as carbon dynamics changes over time, mostly due to changes in the availability of different roundwood products over time and their utilization for manufacturing various finished wood products.

Methods

We selected loblolly pine (Pinus taeda L.), a commercially important species of the region, as a representative species for ForBioCAM 1.0. The carbon pools accounted in ForBioCAM include biogenic carbon emissions, direct life-cycle carbon emissions during manufacturing, transportation, and combustion of wood pellets, and carbon stored in wood products and wood present in landfills. Additionally, we measured and compared the carbon intensity of wood pellet-based electricity relative to the carbon intensity of coal-based electricity on per unit energy and land bases. In ForBioCAM 1.0, we have not incorporated market-induced impacts on the carbon intensity of wood pellets over space and time (Wang et al 2015, Galik and Abt 2016).
We used a growth and yield model of loblolly pine (Gonzalez-Benecke et al 2011) to ascertain the availability of roundwood products (pulpwood, ‘chip-n-saw’, and sawtimber) at the time of thinning (15th year of plantation) and harvesting (25th year of plantation). We assumed that logging residues are 10% of available roundwood products at the time of thinning and harvesting. The obtained yields of roundwood products and logging residues are reported in figure 1. As expected, the yield of larger diameter roundwood products (e.g. sawtimber) increases, whereas the yield of smaller roundwood products (e.g. pulpwood) decreases with the stand age, as trees continuously gain height and girth with stand age.

For the stand-level perspective, we did not consider ‘first carbon debt and then dividend’ (Walker et al 2012, Jonker et al 2014, Ter-Mikaelian et al 2015) as this approach assumes that biogenic carbon emissions from burning wood pellets will be compensated by plantation growth over time. This assumption treats carbon sequestered in a forest stand and biogenic carbon emission released due to the burning of wood pellets as a part of the same carbon pool, but they are two different carbon pools and must be aggregated only at a system level in the presence of other carbon pools. If there is no additional growth (relative to growth and yield of stand with the baseline case) in the stand after harvesting roundwood for production of wood pellets, which is carbon equivalent to the net difference between biogenic carbon emission and carbon saved due to the displacement of coal-based electricity, then the ‘first carbon debt and then dividend’ approach does not accurately depict the carbon dynamics, especially when multiple rotations are considered.

We selected a system boundary for determining the carbon intensity of electricity generated in the UK from imported wood pellets under the stand and

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**Figure 1.** Growth and yield of roundwood products and residues relative to stand age. At the time of thinning (stand age 15 years), a total of 0.0, 8.2, 33.8, and 4.2 Mg/ha of sawtimber, chip-n-saw, pulpwood, and logging residues were obtained, respectively. Corresponding values are reported in table S1 (available online at stacks.iop.org/ERL/14/024006/mmedia).

**Figure 2.** System boundary for estimating the carbon intensity of electricity generated in the UK using imported wood pellets from the southern United States without considering temporal dynamics.
landscape perspectives (figure 2). Based on the assumptions that half of the available roundwood products, including logging residues, will be converted into wood pellets and that such wood pellets will have only a 5% moisture content, we estimated the total amount of manufactured wood pellets. We used 18 MJ kg$^{-1}$ as the calorific value of wood pellets (Dwivedi et al. 2014b). We calculated the total electricity generated at a power plant (645 MW capacity) from imported wood pellets, using a conversion efficiency of 38.6% (European Commission 2016). The conversion efficiency of high-capacity wood pellet-based power plants (e.g. Drax power station in the UK) is higher than the overall conversion efficiency of 36% for coal power plants at the national level (Digest of United Kingdom Energy Statistics (DUKES) 2018).

For carbon emissions related to the steps present in the supply chain, we used values reported in Dwivedi and Khanna (2014a) for ascertaining the carbon stock for each selected scenario. We obtained carbon sequestered ($x$) at the stand level in an unharvested stand over the simulation period by following Gonzalez-Benecke et al. (2011). We followed Dwivedi and Khanna (2014a) for determining the carbon intensities of electricity generated in the UK from wood pellets imported from the southern United States on land and energy bases.

The system boundary for determining the trajectory of total carbon stock of the TRAD roundwood utilization scenario over the simulation period of 70 years (figure 3). We made suitable changes in the selected system boundary for estimating the total carbon stock of other scenarios (table 1). We used parameters (table S3) for operationalizing the selected scenarios based on Dwivedi et al. (2016). We followed Dwivedi et al. (2014a) for ascertaining the carbon stock for each selected scenario.

For scenarios where wood pellets are manufactured and used to generate electricity, we have accounted for carbon emissions related to the supply chain as well.
To estimate the total carbon stock when the stand is harvested for generating wood pellet-based electricity in a given simulation year $t$, we first estimated the total generated electricity and related biogenic ($y$) and life-cycle carbon ($z$) emissions, based on the quantity of roundwood products available at the time of harvest. We also estimated the amount of carbon savings due to the displacement of coal-based electricity with electricity generated from wood pellets obtained in the same simulation year ($xx$). Additionally, we assumed that the same amount of electricity would have been generated using coal in the absence of wood pellets manufactured from various roundwood products obtained after harvesting the stand. We estimated total carbon emissions related to coal-based electricity in the absence of wood-pellet based electricity ($yy$).

Finally, we calculated the total carbon stock at a harvest year $t$ using the following equation with the stand perspective: displaced carbon emissions ($xx$) at year $t$ minus cumulative carbon emissions by sourcing electricity from coal ($yy$) till $t-1$ years minus biogenic carbon emissions due to the burning of wood pellets ($y$) at year $t$ minus life-cycle emissions ($z$) at year $t$. We have taken the cumulative value of coal-related emissions until $t-1$ years in the absence of any harvest before year $t$, as we are continuously using the equivalent coal-based electricity for each year in which there was no harvest. Then, we subtracted the carbon sequestered in the stand ($x$) from the total carbon stock calculated above and obtained the net carbon stock at year $t$. At the landscape level, we followed a similar approach for estimating the net carbon stock without considering biogenic emissions.

**Results**

**Carbon intensity of wood pellet-based electricity without considering time**

From a stand perspective, the total (biogenic and direct life-cycle) carbon intensity of wood pellets per unit energy at the time of harvesting is 307.02 g C/kWh, of which 80.2% is biogenic carbon emission, and the rest is life-cycle carbon emission (figure 4(A)). This is 29.4% higher than the carbon intensity of coal-based electricity (237.3 g C/kWh) in the UK (http://gridwatch.co.uk/co2-emissions). At the other extreme, from a landscape perspective (assuming biogenic carbon neutrality and accounting for direct life-cycle emissions only), the carbon intensity of electricity generated from imported wood pellets is 60.9 g C/kWh, which is 74.3% lower than the carbon intensity of coal-based electricity in the UK. The carbon intensity of wood pellet-based electricity is independent of the feedstock type used under each of the forest management perspectives at a point in time on per unit energy basis. The stand versus
landscapes perspective led to a similar pattern of difference in the carbon intensity of generated electricity on a per unit land basis (figure 4(B)) as it did on a per unit energy basis. However, the carbon intensity of wood pellet-based electricity differs with the feedstock type and is directly proportional to the amount of biomass used in the manufacture of wood pellets on per unit land basis.

**Total carbon stock per unit land over time**

In the TRAD scenario, the cyclical nature of the trajectory of total carbon stock (figure 5(A)) is explained by the fact that the carbon sequestered in a stand decreases at the time of harvesting and starts increasing after replanting. Simultaneously, the carbon sequestered in wood products and wood present in landfills increases at the time of harvesting and starts decreasing immediately afterwards, due to the decay of wood products and wood present in landfills, until the next harvest replenishes the carbon stock. The diversion of some or all of the biomass to bioenergy (in the BIO-LR, BIO-LR + PW, and BIO-ALL) lowers the carbon stock per unit of land due to higher biogenic carbon emissions than those mitigated by displacing coal; the extent of this increase with the amount of forest biomass diverted for manufacture of wood pellets. Total carbon stock under the BIO-ALL scenario was the lowest among all the scenarios at the end of the simulation period. As the simulation period increases, the trajectories of total carbon stock for the scenarios TRAD, BIO-LR, and BIO-LR + PW increase at a slower rate because carbon sequestered in wood products and wood present in landfills does not decay completely within a rotation, and therefore, carbon from a new harvest cycle is added to the already sequestered carbon from the previous rotation. In contrast with the landscape perspective, the diversion of forest biomass to bioenergy results in a higher total carbon stock relative to the TRAD scenario because of the underlying condition of biogenic carbon neutrality; the BIO-ALL scenario results in the highest level of total carbon stock per unit of land (198.4 Mg C/ha over 70 years) among all the bioenergy scenarios (figure 5(B)).

**No harvest versus harvest over time**

With no harvest, the carbon sequestered in a stand continues to increase and stabilizes at about 282 Mg/ha at the end of the simulation period (figures 6(A)–(D)). The carbon emission to the atmosphere generated due to the foregone use of forest biomass for wood pellet-based electricity increases over time, mostly due to carbon emissions from equivalent coal-based electricity. We found that the net difference in carbon balance in an unharvested stand compared to that with the use of biomass for wood pellets is negative after break-even periods of 32, 18, 10, and two years in the BIO-LR, BIO-PW, BIO-LR + PW, and BIO-ALL scenarios, respectively. This indicates that the carbon stock on land with an unharvested stand is lower over time (e.g. after 32 years

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**Figure 5.** Trajectory of the total carbon stock of selected wood utilization scenarios over time. Under the TRAD scenario, the roundwood products of sawtimber, chip-n-saw, and pulpwood are used as lumber, small lumber, and paper manufacturing, respectively, whereas logging residues are left on the ground. The BIO-LR scenario is the same as the TRAD scenario except for 70% of logging residues being used for wood pellets. The BIO-PW scenario is the same as the TRAD scenario except for 100% of pulpwood being used for wood pellets. The BIO-LR + PW scenario is the same as the TRAD scenario except for 70% of logging residues and 100% of pulpwood being used for wood pellets. Under the BIO-ALL scenario, all roundwood products and 70% of logging residues are used for wood pellets. See table 1 for more details. We track four carbon pools to estimate total carbon stock: carbon in the stand, carbon in wood products, carbon in a landfill, and avoided carbon emissions due to the displacement of coal-based electricity. We also account for carbon released during silvicultural activities (use of fertilizers) and manufacturing of wood products for estimating total carbon stock. We also incorporate transportation-related emissions. See figures S1(A)–(E) and S2(A)–(E) for the breakdown of total carbon balance for scenarios with stand and landscape perspectives, respectively. We also assumed that the hectare of loblolly pine stand is in the Lower Coastal Plains, with a site index of 21.3 meters, and is thinned in the 15th year and harvested (25th year)—a typical management regime in the region. We obtained data on loblolly pine growth and yield, including carbon sequestered on the stand, from Gonzalez-Benecke et al (2011). Sequestered carbon is shown as positive.

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**Figure 6.** Carbon balance for scenarios with stand and landscape perspectives, respectively. We also assumed that the hectare of loblolly pine stand is in the Lower Coastal Plains, with a site index of 21.3 meters, and is thinned in the 15th year and harvested (25th year)—a typical management regime in the region. We obtained data on loblolly pine growth and yield, including carbon sequestered on the stand, from Gonzalez-Benecke et al (2011). Sequestered carbon is shown as positive.
when only logging residues are used to manufacture wood pellets, or two years when whole trees are used to manufacture wood pellets relative to the case when the stand is harvested for the manufacture of wood pellets which are then used to generate electricity which then displaces coal-based electricity, even after accounting for biogenic carbon emissions with the stand perspective. The values for the break-even period when the net carbon becomes negative (carbon stock is higher in the bioenergy scenario than carbon sequestered on the stand) with a landscape perspective are 14, 13, and three years for BIO-PW, BIO-LR + PW, and BIO-ALL, respectively (figures 6(E)–(H)).

**Effect of change in the simulation period and rotation age over time**

An increase in the simulation period from 35 to 70 years increases the total carbon stock in all bioenergy scenarios with both perspectives and all feedstock types relative to TRAD, scenario; an exception is under the BIO-ALL scenario with the stand perspective (table S4). This is due to the release of large quantities of biogenic carbon emissions under BIO-ALL scenario relative to other roundwood utilization scenarios where only a part of the total available roundwood is used for manufacturing wood pellets. Relative to a stand harvested at every 25 years for manufacturing traditional wood products, a change in the harvest age to 20 years or 30 years would lead to lower or higher carbon stocks over time, with stand and landscape perspectives depending upon the scenario selected for the analysis. Typically, carbon stocks are lower with stand perspective whereas the carbon stock are higher with landscape perspective (figures 7(A), (B)). This is because, with a rise in the plantation age, the availability of long-lived roundwood products (sawtimber and chip-n-saw) increases, which in turn sequesters more carbon over time in wood products and wood present in landfills. The total carbon stock is smaller for BIO-ALL with the stand perspective for all the selected stand ages, of 20, 25, and 30 years (figure 7(A)). Again, this difference in net carbon stock is attributed to the accounting of biogenic emissions with the stand perspective. However, this is not the case with the landscape perspective (figure 7(B)), where the net carbon stock is higher under the BIO-ALL scenario for the selected stand ages of 20, 25, and 30 years relative to a plantation harvested every 25 years for the manufacturing of traditional wood products, as we are not accounting for biogenic carbon emissions with the landscape perspective. As the simulation period is increased from 35 to 70 years, the net carbon stock increases with the landscape perspective.

**Discussion**

Our analysis shows that a stand perspective results in a lower net stock of carbon per unit of land with the diversion of forest biomass to wood pellets, compared to its use for the manufacturing of traditional finished wood products, even after accounting for the displacement of coal-based electricity. This is due to the accounting of biogenic emissions released at the time of burning wood pellets first, followed by the fact that wood pellets have a lower calorific value than coal,
resulting in more wood pellets being burnt to produce the same amount of electricity. On the other hand, the underlying premise of a landscape perspective leads to the opposite conclusion, because biogenic emissions are partially or wholly carbon neutral i.e. full offset by carbon uptake by trees, depending on the effect of the demand for bioenergy on forest management practices, including any changes in rotation ages.

With a no-harvest baseline, however, the two perspectives converge in their assessment of the carbon effects for various feedstock types used for manufacture of wood pellets. We show that with either a stand or landscape perspective, using some or all of the biomass for electricity generation will lead to a net higher carbon stock on the land than leaving trees unharvested after a break-even period. The length of the break-even period is shorter when a higher proportion of the tree is used for wood pellets; it is a decade or two with the use of pulpwod, and two to three years with the use of whole trees in the manufacture of wood pellets. These findings are in stark contrast to anecdotal perceptions and existing studies which suggest otherwise (NRDC 2011), primarily because these studies did not consider the cumulative carbon emissions from energy-equivalent coal-based electricity in the case of the no-harvest baseline. These studies consider electricity supplied from renewable sources as a substitute for coal-based electricity, which is unrealistic when considering the current status of technology development, especially when it comes to meeting base load electricity demand.

Irrespective of the forest management perspectives and baselines taken for carbon accounting, our analysis shows that wood pellet-based electricity cannot be carbon neutral when both biogenic and life-cycle emissions are considered. Even the assumption that forest bioenergy is biogenically carbon neutral is correct only under a landscape level perspective, when there is no change in forest management practices due to the additional demand for wood pellets and relative to a baseline where roundwood products are used in the manufacture of traditional finished wood products. Thus, an across-the-board assumption that biogenic carbon emission is neutral because forestlands in the United States are a net carbon sink (USEPA 2018) should be carefully evaluated because it may not hold with forest management scenarios and alternative baselines. We suggest determining carbon neutrality claims at the pellet mill level or at a regional level with suitable safeguards (e.g. carbon neutrality certification), as each mill faces a different set of circumstances within the wood basket, rather than taking a nationwide approach to justify a carbon neutrality claim of biogenic carbon emissions related to the transatlantic wood pellet trade.

**Conclusion**

This analysis leads to the question of which perspective and which baseline are appropriate. A landscape perspective and a baseline where roundwood products are used for the manufacture of finished wood products is appropriate for ascertaining the carbon benefits of the transatlantic wood pellet trade. This is especially true as pellet mills are continuously sourcing most of their feedstock for manufacturing wood pellets from privately owned forestlands in the southern United States. However, a stand level perspective for carbon accounting with a no-harvest baseline is appropriate when forest biomass for bioenergy is sourced from stands managed idiosyncratically by an individual family forest landowner that may otherwise leave the stand unharvested, an atypical case in the southern United States. From either perspective, accounting for the carbon effects of bioenergy requires monitoring for any changes in rotation ages, forest management practices, and land use changes in the wood baskets of pellet mills or at the regional level, as

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**Figure 7.** Net carbon sequestered at the end of two simulation periods (35 years and 70 years) for all the roundwood utilization scenarios over three rotation ages (20 years, 25 years, and 30 years) relative to a roundwood utilization scenario where roundwood obtained from a 25-year old plantation is utilized for traditional purposes only. Emissions are shown as negative and sequestered carbon is shown as positive.
changes across these factors will affect the carbon intensity of wood pellets over time. Our study shows that any assessment of the carbon benefits of wood bioenergy has to be context-specific and accompanied by clarity of underlying assumptions about forest management choices, baselines, feedstocks, expected changes in forest management practices, and temporal scale for carbon accounting. We should also consider other possible alternatives to the woody biomass, as markets for wood-based products are evolving with passing time.

Our study will bring much-needed conceptual clarity to the conditions which determine the carbon benefits related to the transatlantic trade in industrial wood pellets. Our study will also provide a platform for constructive dialogue between bioenergy stakeholder groups for formalizing mechanisms for promoting sustainable wood-based bioenergy development worldwide.

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Author Contributions

PD conceptualized the research, collected the necessary data for modeling, developed the model, and wrote the manuscript. MK conceptualized the research, developed the model, and wrote the manuscript. MF prepared the figures and wrote the manuscript.

Competing Interests

The authors declare no competing interests.

Data and Materials Availability

The model (ForBioCAM 1.0) is available for download from the journal’s website.

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