Evaluation of excess heat potentials using advanced composite curves

Example: Ethanol biorefinery at a repurposed pulp mill site

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Introduction

This paper illustrates the use of advanced composite curves for assessing the potential for excess heat availability at an industrial biorefinery plant. The plant is a repurposed pulp mill producing wood-based ethanol, see Figure 1. Infrastructure and equipment from the pulping process have been repurposed and complemented with new equipment for the production of ethanol. The plant concept was investigated in detail in a PhD project at Chalmers, and the resulting process model represents a potential, well-integrated and energy efficient, industrial-scale biorefinery process. This process is therefore representative of an industrial site that may be realised in Sweden in the future.

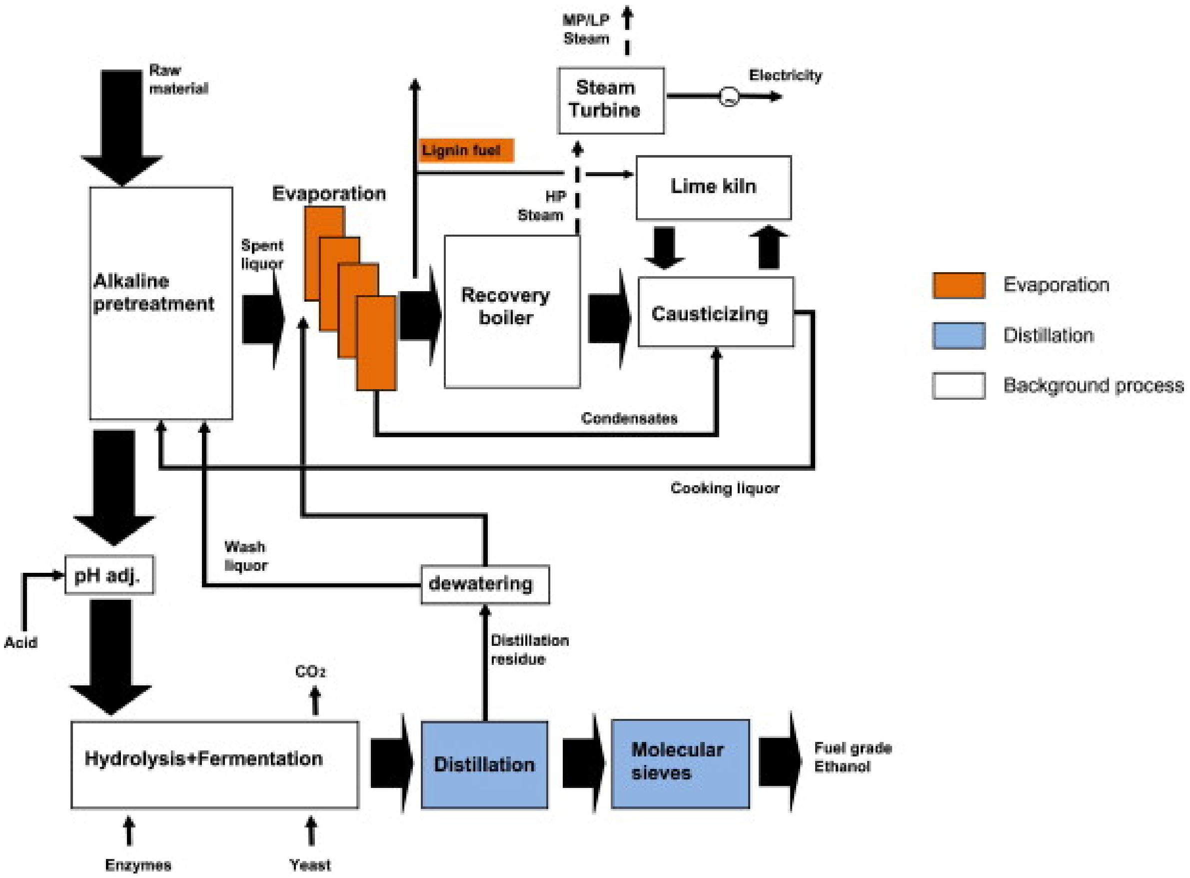

Figure 1. The studied process of a pulp mill converted to an ethanol production plant.

The process concept is described in [1]. Data and more information about the process can also be found in the industrial process data bank [2].

Advanced composite curves - Theory

This paper assumes that the reader is familiar with the basic concepts of advanced composite curves. A short summary of these curves is presented in Table 1. For a more elaborate description of the advanced composite curves and how they are constructed and interpreted, see [3].

Table 1. Advanced composite curves

HUC/CUC	Hot/Cold Utility Curve	Composite curves consisting of utility streams in heaters/coolers
AHLC/ACLC	Actual Heating/Cooling Load Curve	Composite curves consisting of process streams in heaters/coolers
THLC/TCLC	Theoretical Heating/Cooling Load Curve	THLC = Composite curve showing the lowest levels at which hot utility can theoretically be supplied, for a specified heat demand. TCLC = Composite curve showing the highest levels at which excess heat can theoretically be released, for a specified heat demand. The curves are constructed from the process streams in the heat exchanger network
EHLC/ECLC	Extreme Heating/Cooling Load Curve	Composite curves of heat demand/heat release, when vertical heat exchange is implemented in the HEN, i.e. when minimum area is installed

Heat integration in the existing process design

In the process there is a high degree of internal heat recovery. However, the ethanol plant and the distillation plant are not heat integrated with the rest of the process.[i] The heat exchanger network of the background process without the distillation and evaporation sections is shown in Figure 2.

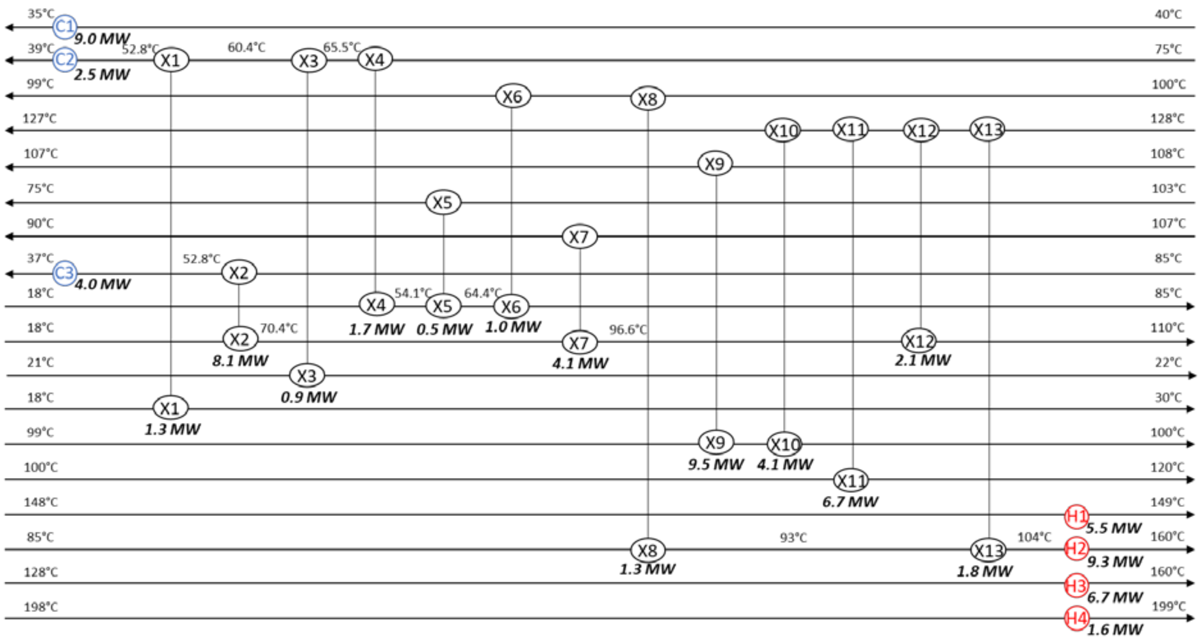

Figure 2. The heat exchanger network of the studied process. Adapted from Fig. 6 in [1].

This network was constructed using a ΔT_{min} of 7 K, which gives a hot pinch temperature of 100°C and a cold pinch temperature of 93°C. Although the network design is very close to achieving maximum energy recovery (MER) for this ΔT_{min}, it is not an ideal MER network. The hot utility demand for this network (23.1 MW) is slightly higher than the minimum hot utility demand for a ΔT_{min} value of 7 K (21.9 MW). This is almost entirely explained by a cross-pinch heat transfer of 1.1 MW found in heat exchanger X7.

A closer look at the heat exchangers in the existing design reveals three heat exchangers of particular interest regarding their ΔT: X8, X9, and X11, which all have temperature approaches of 7-8 K.

The actual hot utility demand of 23.1 MW corresponds to a global ΔT_{min} value of 8.15 K. For this value of ΔT_{min}, the pinch point is changed to approximately 107°C for hot streams and 99°C for cold streams. If the network shown in Figure 2 is analysed considering the pinch temperature of 107°C/99°C, it can be seen that heat exchanger X9 has a negative cross-pinch heat transfer. In other words, it actually transfers heat from below to above the pinch. This is made possible by the fact that the ΔT for this heat exchanger is less than $\Delta T_{min.}$ To balance this, cross-pinch heat transfer (down through the pinch) is found in X12 and X13.

Hence, to summarise, the analysed heat exchanger network has a utility demand that corresponds to a global ΔT_{min} value of 8.15 K, but it is not a true MER network due to the existence of positive and negative cross-pinch heat transfer.

Advanced composite curves - Example

Using the stream data reported in the industry data bank and the information from the heat exchanger network shown above, the advanced composite curves can be constructed. The advanced curves are generated using a global ΔT_{min} of 8.15 K, which corresponds to a minimum heating and cooling demand that is equal to the demand of the network shown in Figure 2. The ΔT_{min} for individual heat exchangers was set to 5 K to illustrate the potential for improvements through tighter heat integration. The resulting curves are shown in Figure 3.

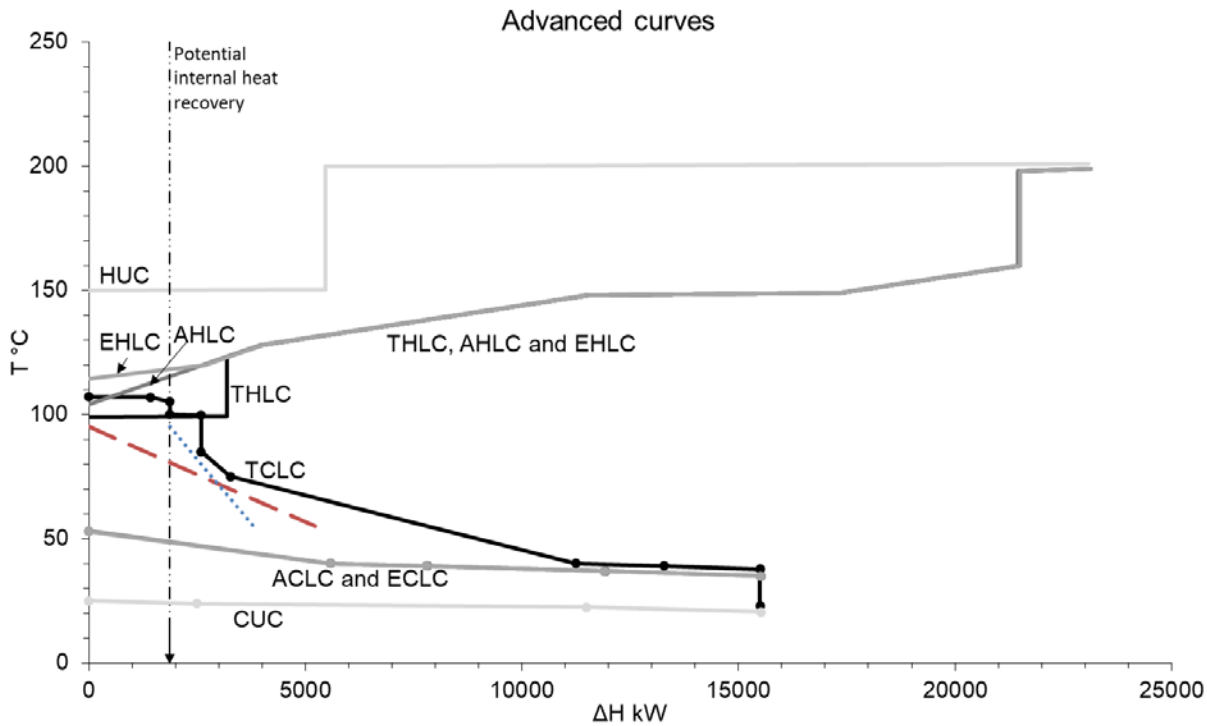

Figure 3. Advanced composite curves for the process at the biorefinery plant (distillation and evaporation excluded). $\Delta T_{min, global}$ = 8.15 K, $\Delta T_{min,HX}$ = 5 K. Dashed red line: Example of excess heat potential if no improvement is made in internal heat recovery. Dotted blue line: Example of excess heat potential when internal heat integration is increased by about 1.9 MW.

Estimating the excess heat potential from the advanced curves

The advanced composite curves show that there is no excess heat available above 53 °C neither directly from utility (CUC) nor from process streams that are cooled by utility in the existing design (ACLC).

However, the TCLC shows that there could be almost 3 MW of heat available above 100 °C if the heat exchanger network is rebuilt[ii]. Together with heat that could be made available at lower temperatures, this could be used, for example, to supply heating to a hot water circuit or district heating system. The amount of excess heat that can be delivered depends on return and supply temperatures. For illustration, a return temperature of 55 °C and a supply temp of 95 °C is assumed, and ΔT_{min} is assumed to be 5 K (red dashed line in Figure 3). This gives a potential for excess heat deliveries of almost 5 MW.

The opportunity to deliver excess heat from the process has to be weighed against the possibility to rebuild the heat exchanger network for internal hot utility savings. The potential for internal heat integration amounts to 1.87 MW. If this heat is recovered internally, the potential for external excess heat deliveries will be reduced to 1.93 MW[iii] (blue dotted line in Figure 3).

The curves also provide some indication about the extent of heat exchanger network modifications that would be required for enhanced internal or external excess heat recovery. In this example, the ACLC is significantly below the TCLC. This indicates that retrofits for external excess heat delivery are likely to require more modifications of the heat exchanger network than if the ACLC would have been closer to the TCLC. In fact, the ACLC overlaps completely with the ECLC, which indicates that coolers are placed as far below the pinch as possible. The expected difficulty of releasing excess heat at high temperatures also means that using this heat for internal heat recovery is likely to be difficult. The extent of the network modifications required for internal heat recovery, however, also depends on the placement of the AHLC in relation to the THLC and EHLC. In this case, it is difficult to draw general conclusions. It is possible that some degree of heat recovery could be achieved with reasonable changes (given that the AHLC is located close to mid-way between THLC and EHLC for ΔH values up to approximately 2 MW), but after that, additional heat savings are likely to require extensive modification of the existing network also above the pinch (AHLC closer to EHLC than THLC).

Comparison with GCC analysis of excess heat

As shown below, a GCC cannot provide the compact overview of internal and external heat recovery options that is provided by the advanced composite curves. One of the difficulties of using the GCC for estimating excess heat potentials is to choose an appropriate value of ΔT_{min}. There are, essentially, two options: A low value of ΔT_{min} that represents the heat available from the process if it would be internally heat integrated, or a higher ΔT_{min} that corresponds to a minimum utility demand that is equal to the current demand. In this example, the two cases would correspond to a ΔT_{min} of 5 K or a ΔT_{min} of 8.15 K.

In a GCC with ΔT_{min} = 5 K, the potential would be read as approximately 1.9 MW, see Figure 4. This is, admittedly, the same potential that was estimated from the TCLC after internal heat recovery was assumed (compare blue dotted line in Figure 4 with blue dotted line in Figure 3). However, this GCC provides no information about how much heat could be delivered if the internal heat integration is not increased. Furthermore, it does not give any indication of the difficulty of the retrofit required.

In a GCC with ΔT_{min} = 8.15 K, the potential would instead be read as approximately 3.7 MW, see Figure 5. This is less than what was indicated by the advanced curves, which was almost 5 MW. One reason for this is that even if this GCC represents the same heating and cooling demand as the current design, it does not represent correctly the specific design of the network.

Furthermore, the representation of shifted temperatures in the GCC makes it difficult to quickly interpret the chart. In Figure 5, the return and supply temperatures of the heating circuit have been shifted up by 8.15 K /2, that is, using the same ΔT_{min} as for the process shown in the GCC. However, we assumed earlier that the ΔT_{min} for heat exchange with the heating circuit should be 5 K. We could consider this to some extent by shifting supply and return temperatures up by 5 K / 2, but the shifting of the process stream temperatures would still not be correct. In this example, the difference is more or less negligible since the ΔT_{min} values are so close. In other examples, when the heating and cooling demand of the current process corresponds to greater values of the global ΔT_{min}, the effect of the problematic representation of temperatures will be much stronger.

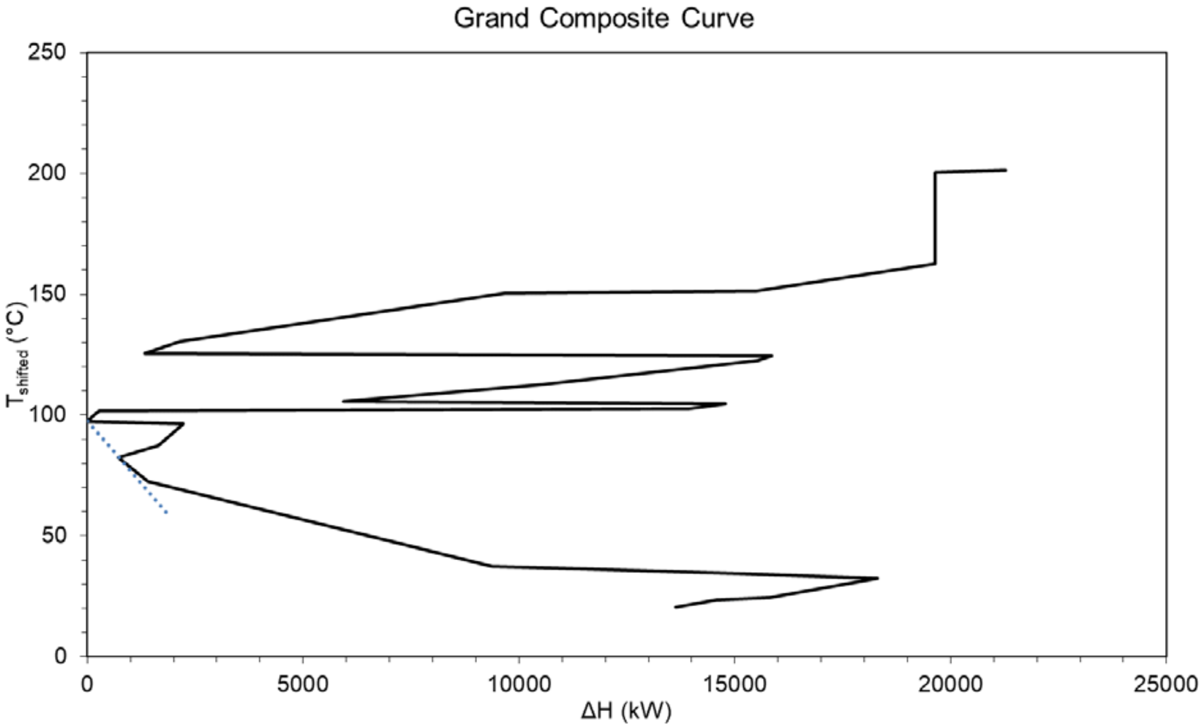

Figure 4. Grand composite curve for the process at the biorefinery plant (distillation and evaporation excluded). ΔT_{min} = 5 K. Blue dotted line: Example of excess heat potential.

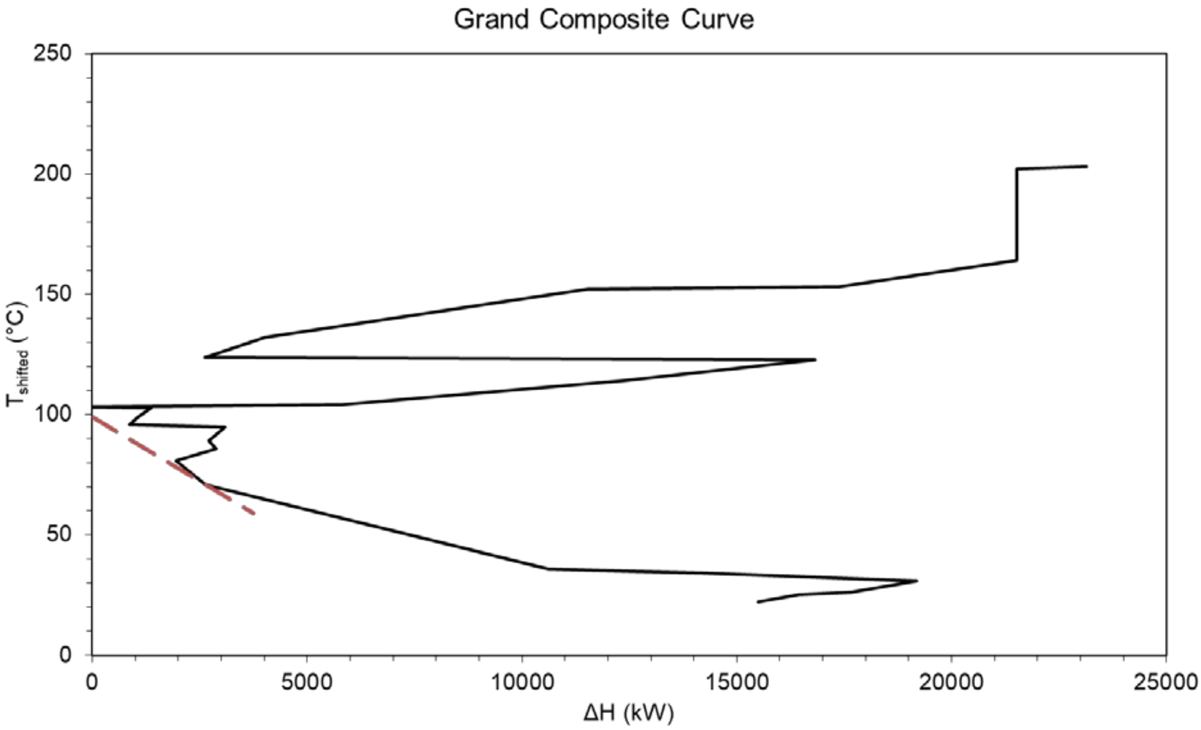

Figure 5. Grand composite curve for the process at the biorefinery plant (distillation and evaporation excluded). ΔT_{min} = 8.15 K. Red dashed line: Example of excess heat potential.

Final remark

Although the studied system is not a real industrial process, the example presented in this paper illustrates how the advanced composite curves can be used to evaluate the potential for external and internal heat recovery retrofits for existing industrial processes. Due to the fact that the studied process was very energy efficient to start with, the potential for heat recovery is not very significant and furthermore, the ΔT_{min} corresponding to the current utility demand is only slightly higher than the minimum ΔT_{min} that is realistic to assume for a retrofit design. As a consequence, different methods used to estimate the potential for heat recovery show no significant difference in the resulting numbers. The principles, nevertheless, remain valid, and for real industrial cases, different methods (i.e. GCC or advanced curves) may result in far more significant differences in estimated excess heat levels.

The studied process is representative of a real process in the way that the existing design includes cross-pinch heat transfer matches, as well as heat exchangers with low ΔTs and thereby large heat transfer areas that may be utilized in the retrofit of the network.

References

[1] Fornell, Berntsson and Åsblad (2012). Process integration study of a Kraft pulp mill converted to an ethanol production plant - Part B: Techno-economic analysis. Applied Thermal Engineering, 42, 179-190, doi:10.1016/j.applthermaleng.2012.02.043.

[2] Repurposed pulp mill example, 2017-11-15. IEA IETS Industrial Process Stream Database, draft template version 1, 2017-09-13.

[3] Nordman and Berntsson (2009). Use of advanced composite curves for assessing cost-effective HEN retrofit I: theory and concepts. Applied Thermal Engineering 29, 275-281.

Notes

[i] This level of heat integration corresponds to Alternative F in [1].

[ii] The heat surplus shown by the TCLC above 105 °C could only be released by retrofitting the heat exchanger network. By retrofitting the network, this heat could in fact be used to cover the heat demand shown by the THLC at 100 °C. This would lead to a reduction of the hot utility demand or, with another perspective, as a potential to release heat at the hot utility temperature level. Consequently, the heat indicated by the TCLC to left of the point to which internal heat recovery would be possible (here approximately 1.9 MW), could have been represented and made available at the hot utility temperature levels.

[iii] This number is either calculated by traditional pinch targeting methods, or by mirroring the TCLC against the THLC in a split GCC analysis.