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SANKEYSIM
MODEL DESCRIPTION, DATA AND SCENARIOS

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Abstract

Sankey diagrams showing the movement of materials through an economy from extraction and imports through production, use, and accumulation to waste generation and disposal have become a key feature in discussions of a circular economy. By lengthening the time that materials are kept within the economy through better design, increased durability, repairability, and sharing, and greater reuse and recycling, the requirements for virgin materials and generation and disposal of wastes can be reduced. All this can be surmised from a Sankey diagram of materials, but it requires a simulation model to quantify the impacts of each of these measures and combinations of them on the materials throughput of an economy. In this working paper, we describe SankeySim, a systems dynamics model of the Canadian economy that calculates the impact on materials throughput of various measures intended to increase the circularity of the Canadian economy. We also describe several scenarios of a Canadian transition towards a circular economy by reaching in 2040: 1) the average performance of the EU in 2017; 2) the performance of France in 2017; 3) the average performance of the EU in 2017 plus net-zero greenhouse gas emissions in 2050.

Introduction

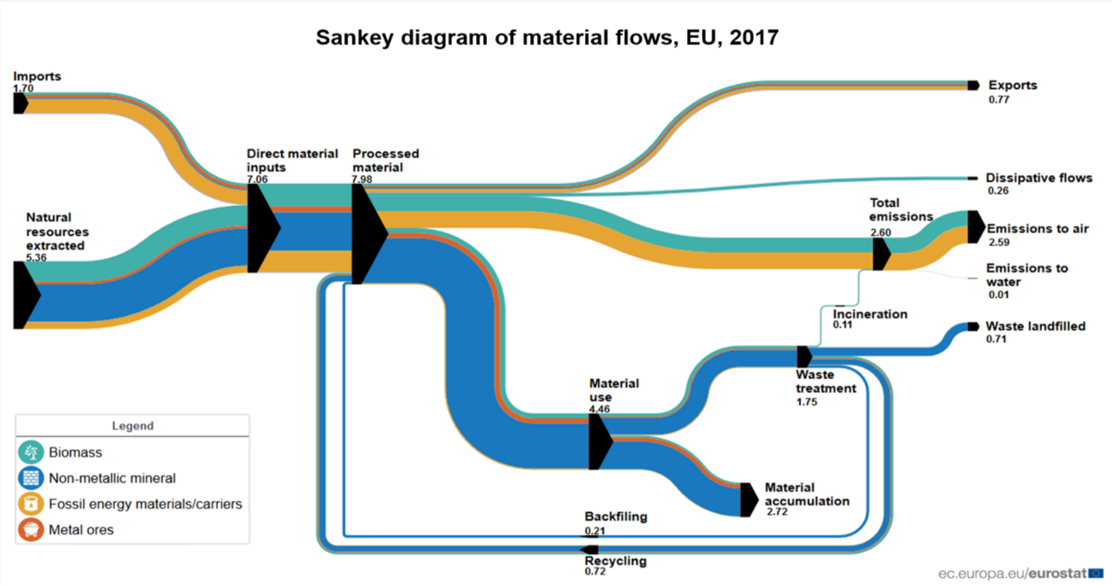
In this paper we provide a detailed description of *SankeySim*[1], a simulation model designed to simulate the impact of changes in several measures that affect the circularity of the Canadian economy and on its use of resources and release of wastes back into the environment. SankeySim was developed to support the work of the Council of Canadian Academies Expert Panel on the Circular Economy in Canada and the preparation of their report *Turning Point* (CCA, 2021)[2]. SankeySim is based on the well-known Sankey diagram that is widely used for illustrating the flow of materials, energy and water through an economy and/or its sub-sectors. Sankey diagrams are an effective way of displaying data on sources, uses and disposition of materials, energy and water. Most of the discussion about making economies more circular focus on materials though measures that affect material flows generally have implications for the use of energy.
Here, we focus on materials.

Figure 1 shows a Sankey diagram of material flows for the European Union (EU) countries. Materials are divided among four categories: biomass, non-metallic minerals, fossil energy materials/carriers, and metal ores.[3]

1 You can run the model via: https://exchange.iseesystems.com/public/petervictor/sankeysim/index.html
2 Available online: https://cca-reports.ca/reports/the-circular-economy-in-canada/
3 See the Glossary for definitions.

Materials enter the EU economy through the domestic extraction of resources and as imports of resources and products. Their sum total is the direct material inputs to the economy. They flow through the economy from left to right. The widths of the bands are proportional to the mass of materials flowing. A key feature of this Sankey diagram is that all of the direct material inputs to the economy are accounted for. Materials are either accumulated within the economy, which means they reside or are stored in the economy for more than a year (material accumulation in the diagram is net of discards and demolition[4]), or they are recycled or used for backfilling, exported, or disposed of back into the environment as a combination of dissipative flows, air and water emissions, and landfill.

Figure 1: Sankey Diagram of Material Flows, EU, 2017 (billion tonnes)



Source: https://ec.europa.eu/eurostat/web/products-eurostat-news/-/DDN-20200311-2

The data in *Figure 1* can be used to calculate a circularity rate based on the ‘share of materials recovered and fed back into the economy [i.e. recycled in domestic recovery plants]’ (Eurostat, 2020). Using this metric, the EU economy had a circularity rate of 11.5% in 2017.[5] This is compared with

4 ‘The difference between inputs and outputs corresponds to the net accumulation of material in the economy in the form of e.g., buildings and infrastructures, machinery and durable goods.’ (EUROSTAT 2018-2 p. 8)

5 Source: https://ec.europa.eu/eurostat/databrowser/bookmark/b223503c-e6d5-4a82-bb41-1bbf336d24d3?lang=en;
Note that the Eurostat circularity rate excludes imported waste destined for recovery and adds exported waste destined for recovery abroad. Equivalent data for Canada are unavailable so the circularity rate calculated in SankeySim does not allow for this refinement. The implicit assumption is that these imports and exports of materials for recovery are equal. For a comprehensive discussion of alternative measures of the circularity rate see Eurostat (2018).

nation-state circularity rates of 29.7% in the Netherlands, 18.8% in France and 6.8% in Sweden. (See table 3 for a complete list of EU circularity rates in 2017). The Sankey diagram raises questions about the implications for material use, waste emissions and circularity of changes in the activities that affect their magnitude. These activities include increased recycling and backfilling, reductions in the material intensity of products through better design, increased product functionality, durability, reuse, repairability and sharing. SankeySim is designed to make this type of assessment possible and to do so for the Canadian economy.

In this paper, we describe the structure of SankeySim and key assumptions used to construct the model. We also explain how we assembled a Canadian database sufficient to draw a Sankey diagram for Canada equivalent in *Figure 1* and to calibrate the model. Finally, we describe four scenarios for the period 2022 to 2040 for Canada. These scenarios show what is possible but they are not forecasts or recommended policy objectives. All scenarios assume an annual rate of economic growth of 1.8%. The first scenario assumes a continuation of the current pattern of materials use and disposition in Canada. The other three scenarios simulate Canadian materials and use and disposition if Canada were to transition to:

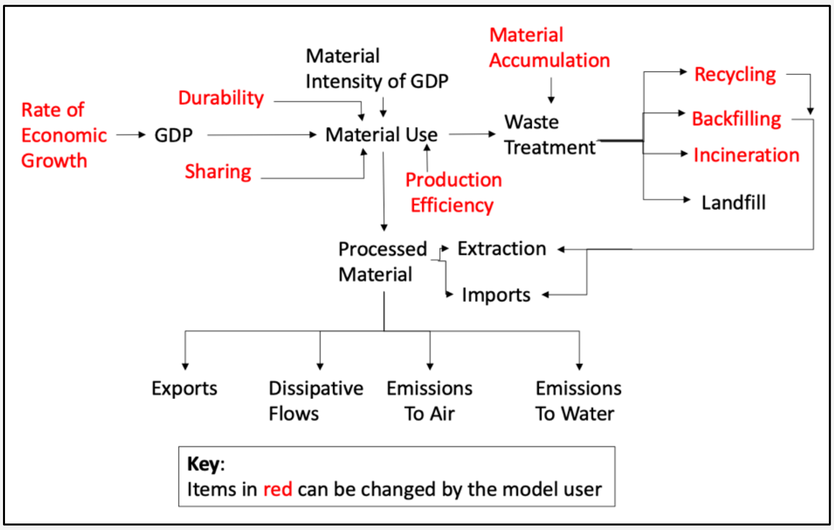
- the average performance of the EU in 2017 over 20 years
- the performance of France in 2017 over 20 years
- the average performance of the EU in 2017 over 20 years plus net-zero greenhouse gas emissions in 2050

The Structure of SankeySim

Figure 2 shows a simplified version of the structure of SankeySim. For purposes of exposition this description is in terms of total material flows (mass). In SankeySim, the identical logic applies to all four categories of materials.

The economic driver of the system is GDP (gross domestic product). The rate of economic growth is shown in red to indicate that its value is set by the model user. GDP multiplied by the *material intensity* of *GDP (tonnes/$)* determines annual *material use* (*tonnes/yr).* Material intensity can be varied in SankeySim by changing *durability, sharing and production efficiency*. (Durability also serves as a proxy for reuse) Each of them reduces the material requirements for a given level of GDP. More durable products and more shared products provide the same level of service to users with reduced materials for any given level of GDP. In SankeySim changes in these variables are applied to the entire GDP when in fact, only some components, capital equipment and consumer durables for example, can be made more durable or shared. Due consideration should be given to this fact when using the model to experiment with changes in durability and sharing.[6]

Figure 2: Simplified Structure of SankeySim



The ratio *processed material/material use* is an indicator of the efficiency of primary materials used to produce processed materials. The multiplication of the ratio by *material use* determines *processed material (tonnes/yr)*. *Material use* (which is net of discards in the EU database) is either accumulated in the economy (i.e., kept in the economy for more than one year, primarily building materials) or 'consumed' and then sent to *waste treatment (tonnes/yr)* where it is divided among *recycling, backfilling, incineration* and *landfill (all in tonnes/yr)*. Landfill receives whatever remains after the other three possibilities have been calculated based on historical proportions that can be modified by the model user.

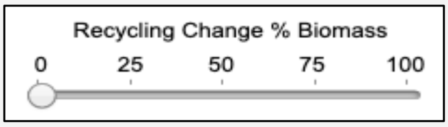
Wastes that are recycled or backfilled reduce *extraction* and *imports*. Recycled materials re-enter the production process whereas backfilled materials are used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials. *Processed material* that is not included in *material use* is exported, disposed of as *emissions to air*, *emissions to water*, or *dissipative flows (all in tonnes/yr)* based on historical proportions as modified by the model user.

The model user can change the values of the following variables for each of the four categories of material by moving the appropriate slider as shown in

6 It is possible that increasing durability will result in increasing material accumulation, but this is not provided for automatically in SankeySim. Model users can allow for this relationship by selecting appropriate values for complementary changes in durability and material accumulation.

Figure 3. The Change % refers to the percentage change in the rate of recycling of biomass in Canada in 2017.

Figure 3: A slider that affects the recycling rate of biomass



There are sliders on the user interface of SankeySim for each of the following:

- The rate of economic growth (default is 1.8%/yr)
- The year in which changes in material flows begin (default is 2022)
- The phase in period for these changes (default period is 20 years), and assumes a linear implementation
- Change in the rate of recycling (default values from 2017), with a range of -20 to 100%
- Change in the rate of backfilling (default values from 2017), with a range of -100 to 100%[7]
- Change in the proportion of waste incinerated (default value from 2017), with a range of -100 to 100%
- Change in durability (default value is 0), with a range of 0 to 50%
- Change in sharing (default value is 0), with a range of 0 to 50%
- Change in material accumulation (default value is 0), with a range of -50 to 25%
- Change in processed material efficiency (default value is zero), with a range of -5 to 5%

SankeySim can also be used to simulate the impact on material flows of a transition from fossil fuels to renewable energy derived from a combination of on and offshore wind turbines and solar photovoltaics. Values for the metals requirements (tonnes/GW) are based on Watari (2019). The ratios of metals in wind and solar technologies to fossil fuels included in SankeySim are: onshore wind 2.5, offshore wind 5.3, and solar photovoltaics 23.6.[8]

A Canadian Materials Flow Database

To calibrate SankeySim for Canada it was necessary to create a database containing all of the data shown in *Figure 1* for Canada. Some data such as

7 The lower bound of -100% for backfilling is to accommodate the much lower rate of recycling in France which is used for comparison with Canada in the scenarios described later in this paper.
8 Comparable data for non-metallic mineral requirements are not available so the same value is used for all energy technologies.

for natural resource extraction and imports are available from published sources but many are not. Unlike Eurostat, the statistical office of the EU, Statistics Canada does not publish comprehensive material flow accounts for Canada. Consequently, it was necessary to estimate the missing values. The main approach used was to multiply the average value for the EU 27[9] in 2017 for each missing value by the relative sizes of GDP in the EU 27 and Canada in 2017. In order to set 2021 as the base year for the simulations it was necessary to allow for the overall increase in Canada's GDP between 2017 and 2021 of 1.5%, based on actual GDP to 2020 and a forecast for 2021 (Plecher 2020)[10]. The Canadian Materials Flow Database for 2021, consisting of actual and estimated data for Canada extrapolated to 2021 is displayed in *Table 1*.

Table 1: Material Flow Database Estimated for Canada – 2021 (est.) (thousand tonnes)

All units in thousand tonnes	Biomass	Fossil fuel	Metal ores	Non metallic minerals	Total	Sources
Initial Extraction	288,209	414,084	204,814	456,553	1,363,660	1
Initial Direct Material Inputs	314,524	497,687	251,195	520,961	1,584,367	1
Initial Exports	110,769	284,316	70,130	48,821	514,036	1
Initial Dissipative Flows	18,961	-	-	3,346	22,307	2
Initial Emissions to Air	115,904	125,673	526	1,067	243,171	3
Initial Emissions to Water	859	-	-	4	863	2
Initial Incineration	6,555	1,928	535	1,069	10,088	2
Initial Material Accumulation	60,378	85,315	179,851	442,641	768,186	4
Initial Recycling	13,382	2,786	8,060	45,164	69,391	2
Initial Backfilling	91	165	20	46,914	47,190	5
Initial Processed Material	327,997	500,638	259,275	613,039	1,700,949	4
Initial Material Use	81,504	90,649	188,618	559,800	920,571	4

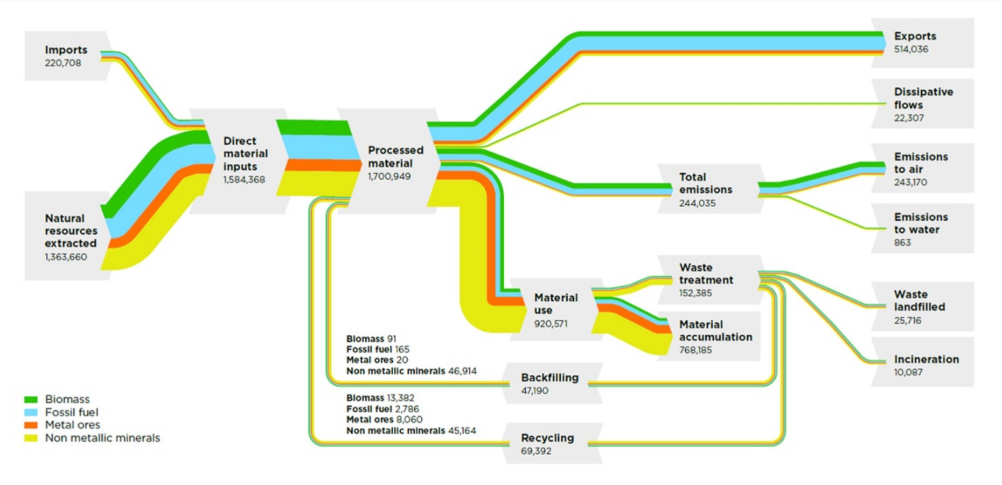
Sources: 1) International Resources Panel; 2) From EU27 GDP extrapolation; 3) Environment Canada; 4) Calculated from other data; 5) From EU27 ratio of backfilling to domestic material inputs

It is stressed that some of the data in table 1 are estimates only. The estimations were constrained by two factors. First, the data for extraction and imports comes from the International Resource Panel (2020) so they are reasonably reliable. They provide the total inflow of materials. The subsequent flows of materials through the economy in the database are consistent with this total. A second constraint satisfied by the values in the database is that the values for material flows entering each node in the Sankey diagram (i.e., the right facing black arrowheads in *Figure 1*) equal the quantities that leave. This condition is met for each of the four types of

9 The EU 27 refers to the 27 member countries of the EU excluding the UK
10 This small increase in Canada's GDP between 2017 and 2021 is due to the Covid-19 pandemic.

material individually as well as in total. *Figure 4* shows a Sankey diagram for material flows in Canada for 2021 based in these data.

Figure 4: Sankey Diagram of Estimated Material Flows, Canada, 2021 (thousand tonnes)



A Canadian Materials Flow Database

The main purpose of SankeySim is to estimate the impact of changes to the quantities and flows of materials as they move through the economy stemming from economic growth and changes in key circulatory measures (the variables) that are affected by policy, business practices and consumer behaviour (e.g. sharing). Sankeysim does not simulate the link between policy and behaviour but starts from the change in behaviour (e.g. more recycling) that a policy is intended to achieve.

Table 2 provides in the first three columns a summary of policies in the public and private sectors intended to promote circularity at various stages in the value chain and their expected effects on circularity. The fourth column explains how these effects on circularity can be simulated in SankeySim and the fifth column describes what to expect from the simulation. Note, the effect on material flows of combinations of policies can be different from the sum of the changes simulated individually given contradictory or overlapping influence of policies that shrink the potential, or conversely complementary impacts that expand the benefits. For example, an increase in product durability can reduce the availability of wastes for rate of recycling.

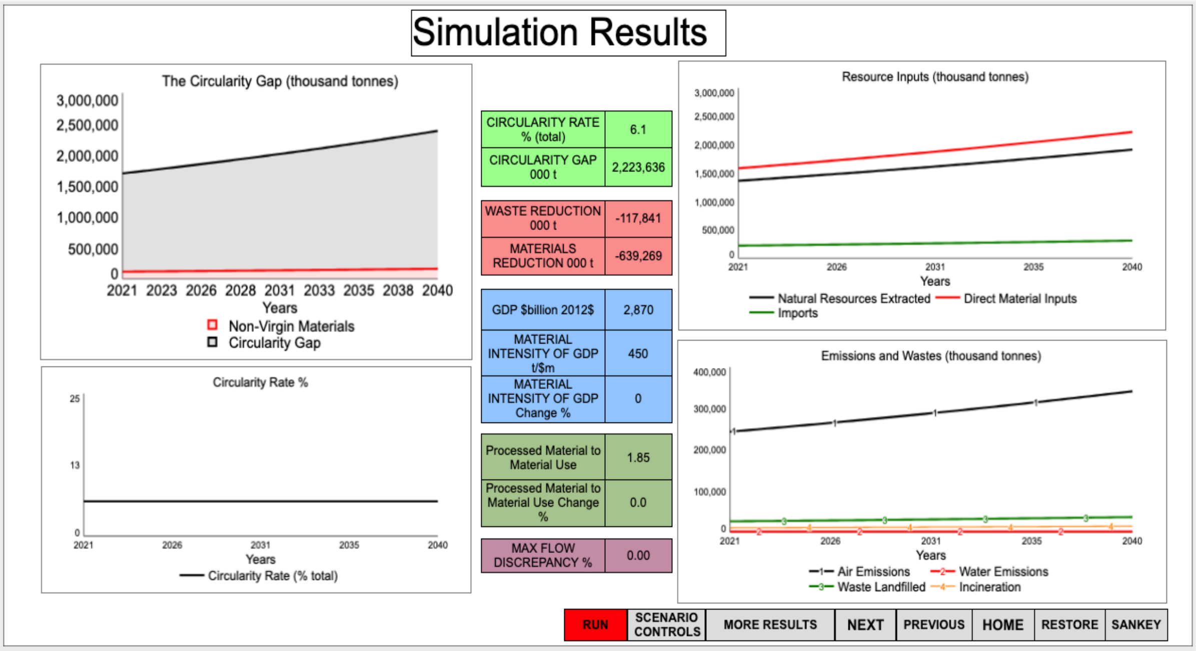
Table 2: Value Chain, Policies and Circularity

Value chain steps	Policies intended to promote circularity	Effects on circularity	Simulate in SankeySim	What to expect
Primary and secondary material production	Material standards	Increase product quality and durability	Durability slider	Reduction in materials and waste. No change in circularity %. Reduction in circularity gap tonnes
	Resource efficiency	Decrease need for virgin material	Production efficiency slider	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity gap tonnes
	Intensity targets	Decrease need for virgin material		
Design	Combined material and energy efficiency	Optimize material and energy use	Durability and Material Accumulation sliders	Reduction in materials and waste. Reduction in circularity gap tonnes.
	Modularity	Increase product life by being repairable		
	Design for durability	Increase product life		
	Design for disassembly	Increase product life by being repairable		
	Life cycle design	Increase product life by being repairable and recyclability		
Production	Tax reform	Increase incentive to adopt CE approaches	Recycling and Backfilling sliders	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity gap tonnes.
	Industry capacity building	Increase capacity to produce CE products		
	Extended producer responsibility	Increase incentive to adopt CE approaches		
Sales	Tax reform	Increase the incentive to choose CE products Reduces virgin material and energy use	Recycling and durability sliders	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity gap tonnes
	Labelling and certification	Increase the incentive to choose CE products Reduces virgin material and energy use		
	Information and awareness	Increase the incentive to choose CE products Reduces virgin material and energy use		
	Public/private Sustainable procurement	Increase the incentive to choose CE products Reduces virgin material and energy use		
Use	Sharing economy	Reduce production, and in turn extraction and emissions	Sharing slider	Reduction in materials and waste. No change in circularity rate %. Reduction in circularity gap tonnes
	Product –service systems	Reduce production, and in turn extraction and emissions		
Waste	Waste targets, bans and landfill fees	Limit the amount of allowed waste	Recycling slider and Backfilling sliders	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity circularity gap tonnes.
	Waste avoidance	Reduces the amount of waste, optimize production	Recycling and Backfilling sliders; Production efficiency slider	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity gap tonnes.
	Re-use	Increase re-use	Durability slider	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity gap tonnes
	Remanufacturing	Increase remanufacturing		
	Recycling	Increase recycling	Recycling slider	Reduction in materials and waste. Increase in circularity rate %. Reduction in circularity gap tonnes.

An example of the output from a simulation using SankeySim is shown in *Figure 5*. It displays the main results for the first of the four scenarios described above: a continuation of the current pattern on materials use and disposition from 2022 to 2040 assuming an annual rate of economic growth of 1.8%/yr. It may be helpful to refer back to *Figure 4* when reading what follows.

The upper graph on the left-hand side of *Figure 5* shows the widening circularity gap (i.e. the difference between total processed material and the contribution of non-virgin materials from recycling and backfilling.) The lower graph on the left-hand side shows the unchanging circularity rate. The upper graph on the righthand side show the direct material inputs into the Canadian economy comprised of natural resources extracted in Canada and imports, and the discharge of wastes divided among the four categories.

Figure 5: An Example of Simulation Results from SankeySim: *Scenario 1* A continuation of the current pattern on materials use and disposition from 2022 to 2040 assuming an annual rate of economic growth of 1.8%/yr.



The light green panel in the middle of *Figure 5* shows two measures of circularity in 2040 – the circularity rate % and the circularity gap in thousand tonnes. The red panel shows the size of the circularity gap in thousand tonnes in 2040 and the quantities of waste reduction and materials reduction. In this scenario these values are negative indicating an increase in wastes and materials used as would be expected in the absence of measures to counteract the effects of an expanding economy on material flows. The blue panel shows Canadian GDP in billions of constant 2012 dollars in 2040 based on the assumed annual growth rate. It also shows the material intensity of GDP and the change in that intensity which is zero given the assumptions used in this scenario.

In the darker green panel values for the ratio of processed material to material use and the change in this ratio are shown. The final panel in purple shows ‘Max Flow Discrepancy’. This metric compares the materials entering the economy with their disposition. A value of 0% indicates that all materials are accounted for in the simulation.

Simulation of Circularity Scenario

SankeySim can be used to simulate a wide variety of scenarios in which the material flows of the Canadian economy are affected by changes in key variables. The simulations described in this paper are:

Scenario 1: continuation of the current pattern of materials use and disposition

Scenario 2: material flows and disposition if Canada transitions over 20 years to the average performance of the EU27 in 2017

Scenario 3: material flows and disposition if Canada transitions to the performance of France in 2017 over 20 years (France is a leader in the EU27, the main difference being a much higher recycling rate)

Scenario 4: the same as scenario 2 but with the addition of a net zero[11] target for greenhouse gas emissions in 2050 by replacing energy from fossil fuels with energy from renewable sources which have different requirements for materials.[12]

The Sankey diagrams for the four scenarios in 2040, the final year of the simulations are presented together for ease of comparison at the end of the document. These scenarios should not be interpreted as specific goals or objectives for Canada but simply as reference points and examples of how the model can be used. Relevant values for all EU countries in 2017 against which Canada is compared are shown in *Table 3*. The first column shows the circularity rates. This can be compared with the estimated value of 6.1% for Canada (recalling the fact that, unlike the EU circularity rates the Canadian

11 For the purposes of this paper, net zero is defined as the elimination of fossil fuels from Direct Material Inputs

12 For simplicity and because the necessary data with the EU are unavailable in each scenario the same values for the key variables affecting material flows such as the change in the recycling rate are used for each of the four streams: biomass, fossil fuels, metal ores and non-metallic minerals.

estimate does not account for differences in imported waste and exported waste destined for recovery). The other columns show the percentage difference between Canada and the EU and member countries for the variables that affect the circularity rate, circularity gap, and material use and disposition. They are not broken down by the four categories of materials.

Table 3: Circularity Rate for EU27 and Member Countries 2017 and Values for Contributing Factors in Comparison with Canada[13]

	Circularity Rate %	Recycling Change %	Backfilling Change %	Incineration Change %	Material Accumulation Change %	Materials Intensity of GDP Change %	Processed Material to Material Use Change %
EU27	11.5%	-9%	-62%	-9%	-28%	-55%	-3%
France	18.8%	46%	-59%	-75%	-29%	-58%	0%
Netherlands	29.7%	88%	-100%	-76%	-71%	-81%	255%
Sweden	6.8%	-72%	-87%	-98%	-51%	-19%	-12%
Belgium	20.4%	60%	-100%	-49%	-12%	-70%	133%
Bulgaria	3.5%	-92%	-100%	2444%	-100%	33%	-9%
Czechia	7.9%	16%	-10%	-94%	-3%	-47%	23%
Denmark	8.0%	46%	-64%	-100%	-3%	-41%	7%
Germany	11.5%	-3%	-1%	-89%	-29%	-64%	33%
Estonia	12.6%	-44%	-70%	-100%	-72%	17%	28%
Ireland	1.7%	-74%	67%	-99%	-9%	-76%	60%
Greece	2.8%	-84%	-96%	-100%	-96%	-64%	61%
Spain	8.9%	14%	-83%	-98%	-20%	-75%	49%
Croatia	5.0%	17%	-87%	-100%	5%	-49%	16%
Italy	18.4%	98%	-100%	-85%	-20%	-72%	12%
Cyprus	2.4%	-68%	-12%	-100%	4%	-24%	-14%
Latvia	5.5%	75%	-91%	-100%	10%	-50%	85%
Lithuania	4.5%	-26%	-86%	-99%	6%	-29%	29%
Luxemburg	10.6%	20%	32%	-100%	-34%	-51%	0%
Hungary	6.9%	36%	-84%	-92%	3%	-33%	3%
Malta	6.5%	-59%	130%	-95%	-18%	-50%	-11%
Austria	11.6%	45%	-30%	-97%	-14%	-51%	17%
Poland	9.9%	5%	-28%	-96%	-13%	-4%	-11%
Portugal	2.0%	7%	-73%	-96%	11%	-26%	-9%
Romania	1.7%	-92%	-99%	-99%	-54%	11%	-17%
Slovania	5.1%	11%	36%	-97%	-15%	-43%	26%
Sweden	6.8%	-9%	-65%	-92%	2%	-41%	17%
Finland	5.6%	-79%	-96%	-99%	-62%	18%	-18%

Note: the incineration change for the EU27 is based on the amount of waste incinerated that is shown in *Figure 1* which is significantly higher than the

13 Sources:
Circularity rate for EU27: Eurostat, Circular material use rate
https://appsso.eurostat.ec.europa.eu/nui/show.do?query=BOOKMARK_DS-876467_QID_17DA6464_UID_-3F171EB0&layout=TIME,C,X,0;GEO,L,Y,0;UNIT,L,Z,0;INDICATORS,C,Z,1;&zSelection=DS-876467UNIT,PC;DS-876467INDICATORS,OBS_FLAG;&rankName1=UNIT_1_2_-1_2&rankName2=INDICATORS_1_2_-1_2&rankName3=TIME_1_0_0_0&rankName4=GEO_1_2_0_1&sortC=ASC_-1_FIRST&rStp=&cStp=&rDCh=&cDCh=&rDM=true&cDM=true&footnes=false&empty=false&wai=false&time_mode=ROLLING&time_most_recent=true&lang=EN&cfo=%23%23%23%2C%23%23%23.%23%23%23;
Recycling change, backfilling change, and incineration change: Eurostat, Management of waste by waste management operations and type of material—Sankey diagram data) http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_wassd&lang=en;
Material accumulation change, and processed material to material use change: Eurostat: Material flows for circular economy—Sankey diagram data http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ac_sd&lang=en;
Materials intensity of GDP change: GDP PPP (constant 2017 international b$) from World Bank Data, GDP, PPP (constant 2017 international $) | Data (worldbank.org) and Material Use from Eurostat: Material flows for circular economy—Sankey diagram data
http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ac_sd&lang=en

value obtained from summing the individual country values in the database on which this table is based.

The assumptions and scenario results estimated for 2040 are summarized in *Table 4*.[14]

Table 4: Scenario Assumptions and Results

MODEL SETTINGS	Scenario 1 BAU	Scenario 2 EU	Scenario 3 France	Scenario 4 EU plus Net Zero
Rate of economic growth %	1.8	1.8	1.8	1.8
Year Change begins	2022	2022	2022	2022
Phase in period yrs	20	20	20	20
Change in Recycling %	0	-9	46	-9
Change in Backfilling %	0	-62	-59	-62
Change in Incineration %	0	-9	-75	-9
Change in Durability %	0	30	33	30
Change in Sharing %	0	30	33	30
Change in Production Efficiency %	0	30	33	30
Change in Material Accumulation	0	-28	-29	-28
SIMULATION RESULTS in 2040	**Scenario 1 BAU**	**Scenario 2 EU**	**Scenario 3 France**	**Scenario 4 EU plus Net Zero**
Circularity Rate %	6.1	14.4	21.3	20.3
Circularity Gap 000 t	2,223,636	988,421	881,541	1,549,419
Waste Reduction 000 t	(117,841)	38,715	75,654	77,786
Materials Reduction 000 t	(639,269)	595,947	702,828	34,949
GDP $billions (2012$)	2,870	2,870	2,870	2,870
Material Intensity of GDP t/$m	450	212	199	443
Material Intensity of GDP Change %	-	(53.0)	(56.0)	(2.0)
Processed Material to Material Use	1.85	1.85	1.85	1.46
Processed Material to Material Use Change %	0	0	0	(21)

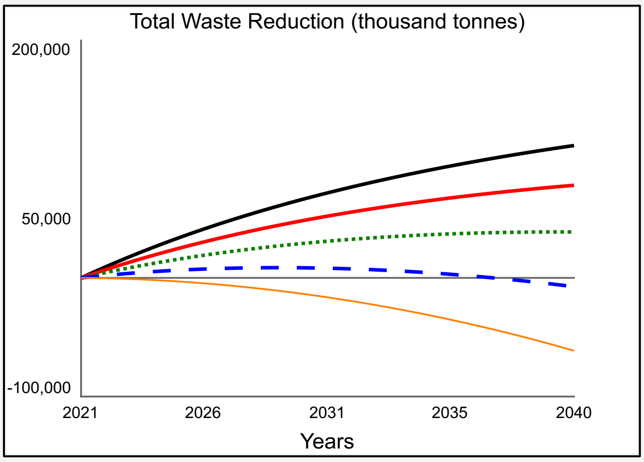
Table 4 shows that if the Canadian economy grows at 1.8%/year to 2040 with no increase in circularity in 2040 wastes will increase by an estimated 118 million tonnes (waste reduction equal to -117,841 tonnes) and material use from extraction and imports will increase by an estimated 640 million tonnes. The circularity rate remains unchanged at 6.1%. Under the second scenario where Canada matches the EU as of 2017 in circularity measures, Canada's circularity rate will rise to an estimated 14.4%, wastes will be reduced by 39 million tonnes and material use reduction will be 596 million tonnes. In the third scenario where Canada achieves rates in 20 years comparable to France in 2017, Canada's circularity rate increases to 21.3%, waste reduction is an estimated 76 million tonnes and materials use reduction 703 million tonnes. The effect of Canada transitioning to net zero greenhouse gas emissions has significant implications for material flows largely because the material requirements for 1gigawatt of energy derived from wind and solar energy are considerably higher than for fossil fuels.

14 Changes in the material intensity result from changes in the values for durability, sharing and production efficiency. The values selected for these variables in the scenarios give the changes in material intensity of GDP based on the date for Canada compared to the EU.

Compared to scenario 2, scenario 4 shows an increased circularity rate to 20.3%, and a much-increased circularity gap in terms of tonnage of materials. Waste reduction is increased reflecting the decline in GHG emissions, but materials reduction while still positive is much lower in scenario 4 than scenario 2 and the material intensity of GDP is only slightly reduced from the BAU case.

SankeySim can be used for sensitivity analysis. *Figure 6* shows how changes in the rate of economic growth imposed on scenario 2 affect waste reduction:

Figure 6: Waste Reduction in Scenario 2 with changes in the Rate of Economic Growth



Rate of Economic Growth
Key: 0.0%
0.9 %
1.8%
2.7%
3.6%

Figure 6 shows that waste reduction varies inversely with the rate of economic growth. The faster the economy grows without any other changes that affect the use and disposition of materials the greater are the materials used and wastes generated.

Table 5 shows equivalent directional relationships between all of the circular economy variables in SankeySim and the main indicators of circularity, waste and materials.[15] An arrow to the right signifies no change.

15 Waste generated and materials used are in columns 5 and 6. respectively rather than reductions for ease of interpretation.

Table 5: Relationships between circular economy variables and indicators of circularity

Change \ Effect	Circularity Rate %	Circularity Gap %	Circularity Gap 000 t	Waste Generated 000 t	Materials Used 000 t
Rate of Economic Growth	→	→	↑	↑	↑
Recyling	↑	↓	↓	↓	↓
Backfilling	↑	↓	↓	↓	↓
Incineration	→	→	↑	↓	→
Durability	→	→	↓	↓	↓
Sharing	→	→	↓	↓	↓
Production Efficiency	→	→	↓	↓	↓
Material Accumulation	↓	↓	↑	↓	↑
Processed Material Efficiency	↑	↓	↓	↓	↓
Fossil Fuel Reduction	↓	↑	↑	↓	↑

Legend:

constant	increase	decrease
→	↑	↓

Limitations of SankeySim

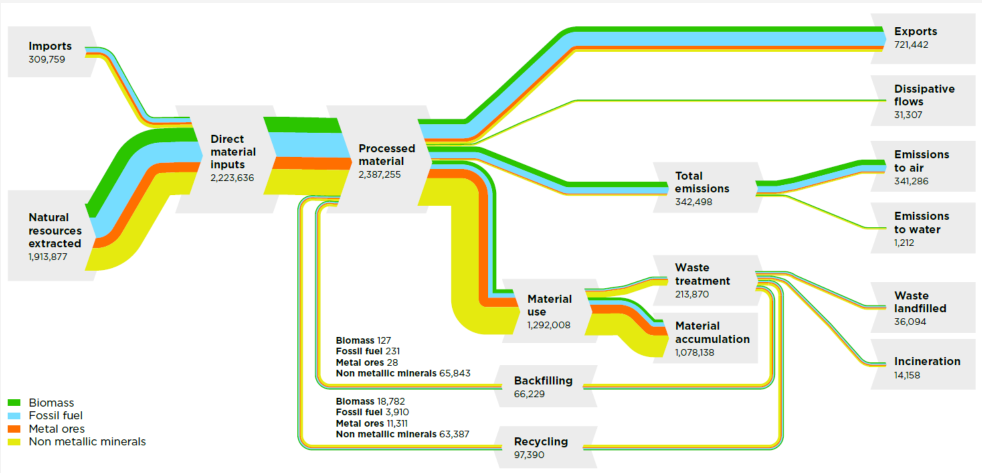
All models are simplifications of what they are intended to represent. The choice of what to include and what to omit should be guided by the purpose of the model. In the case of an empirical model like SankeySim, the simplifications are also influenced by the available data yet then a model can be useful in helping identify what additional data should be gathered.

The main purpose of SankeySim is to show how the material use and disposition in the Canadian economy would change in response to various circularity measures. (Energy and water are not included although a similar approach could be used for modelling them.) With this purpose in mind the most important limitations of SankeySim are as follows:

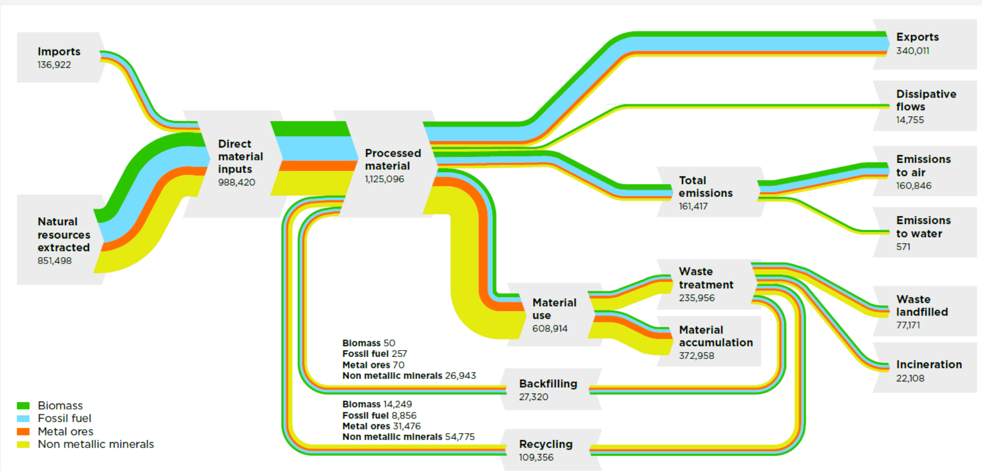
- The lack of a comprehensive Canadian material flow database necessitated the creation of a database consisting of some real data and some estimates based on comparisons with the EU economy.

- The high level of aggregation in terms of materials (four subcategories), geography (no sub-national differentiation), and economic sectors (none explicitly identified).
- No distinction is made between goods and services when the former are more directly related to material flows.
- No allowance is made for the import of recovered materials and export of materials destined for recovery as in the EU statistics.
- Economic, environmental and social costs and benefits of the various circularity measures are not included.

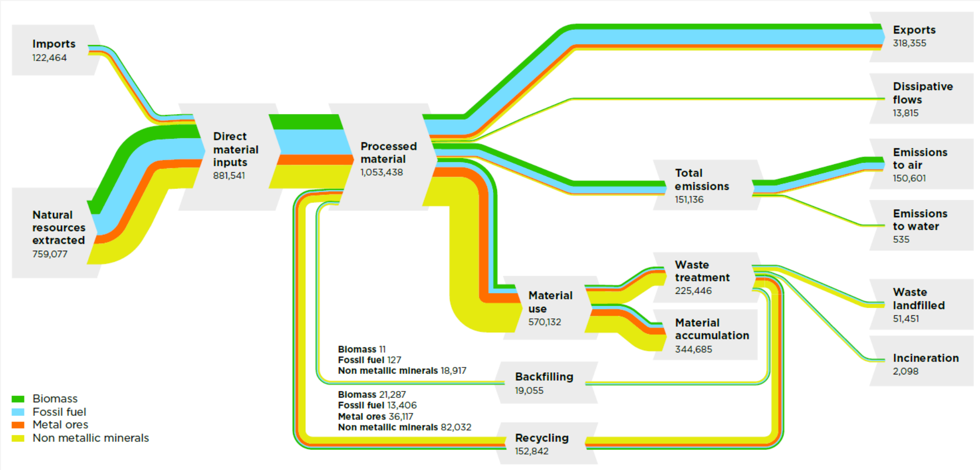
Sankey Diagram for Scenario 1: material flows and disposition in 2040 with continuation of the current pattern of materials use and disposition



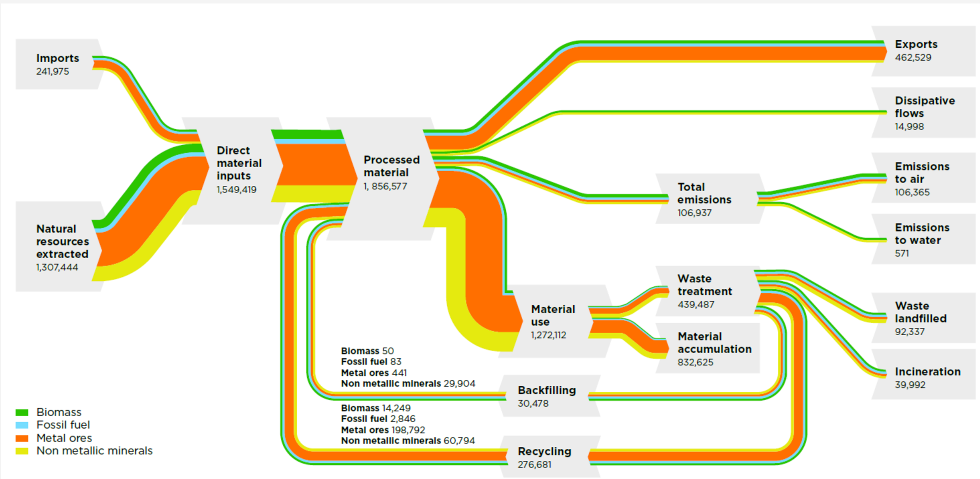
Scenario 2: material flows and disposition in 2040 if Canada transitioned over 20 years to the average performance of the EU27 in 2017



Scenario 3: material flows and disposition in 2040 if Canada transitioned to the performance of France in 2017 over 20 years (France is a leader in the EU27, the main difference being a much higher recycling rate)



Scenario 4*:* material flows and disposition in 2040 the same as scenario 2 but with the addition of a net zero target for greenhouse gas emissions in 2050 by replacing energy from fossil fuels with energy from renewable sources which have different requirements for materials.



Glossary

All Definitions are Extracted from Eurostat (2021).

Backfilling means a recovery operation where suitable waste is used for reclamation purposes in excavated areas or for engineering purposes in landscaping and where the waste is a substitute for non-waste materials.

Biomass is organic, non-fossil material of biological origin (plants and animals) used as a raw material for production of biofuels. It can be also called biomass feedstock or energy crops. It includes wide range of materials harvested from nature or biological portion of waste. The most typical example is wood (firewood, wood residues, wood waste, tree branches, stump, wood pellets, ...), which is the largest biomass energy source. Other examples of biomass are grass, bamboo, corn, sugarcane, animal waste, sewage sludge and algae. Using biomass as a fuel is deemed carbon neutral as carbon was trapped from the atmosphere during the biomass life cycle (its growth). There are several sustainability concerns related to the use of biomass as fuel.

The circularity rate measures the contribution of recycled and recovered materials towards the overall use of materials. The circularity rate is the share of material resources used in the economy which came from recycled products and recovered materials, thus saving primary raw materials from being extracted. A higher circularity rate means that more secondary materials replace primary raw materials, thus reducing the environmental impacts of extracting primary material.

Direct Material Input (DMI) measures the direct and actual input of materials into a given national economy originating from the natural environment or from the rest of the world. It includes the total amount of materials (excluding bulk material flows such as water and air) which are of economic value and are available for the national economy's production system. DMI represents the total material throughput or material scale of an economy. DMI of a given national economy is calculated as the sum of domestic extraction plus physical imports

Domestic extraction, abbreviated as **DE**, is the input from the natural environment to be used in the economy. DE is the annual amount of raw material (except for water and air) extracted from the natural environment.

Domestic material consumption, abbreviated as **DMC**, measures the total amount of materials directly used by an economy and is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports.

Exports to the rest of the world economy from the domestic economy.

Fossil fuel is a generic term for non-renewable energy sources such as coal, coal products, natural gas, derived gas, crude oil, petroleum products and non-renewable wastes. These fuels originate from plants and animals that existed in the geological past (for example, millions of years ago). Fossil fuels can be also made by industrial processes from other fossil fuels (for example in the oil refinery, crude oil is transformed into motor gasoline). For decades fossil fuels satisfy most of the human energy requirements. Fossil fuels are carbon-based and their combustion results in the release of carbon into the Earth's atmosphere (carbon that was stored hundreds of millions years ago). It is estimated that roughly 80% of all manmade $CO_2$and green-house gas emissions originate from fossil fuels combustion.

Imports are flows of products from the rest of the world economy into the domestic economy

Incineration is a method of waste disposal that involves the combustion of waste. It may refer to incineration on land or at sea. Incineration with energy recovery refers to incineration processes where the energy created in the combustion process is harnessed for re-use, for example for power generation. Incineration without energy recovery means the heat generated by combustion is dissipated in the environment.

Landfill is the deposit of waste into or onto land. It includes specially engineered landfill sites and temporary storage of over one year on permanent sites. The definition covers both landfill in internal sites, i.e. where a generator of waste is carrying out its own waste disposal at the place of generation, and in external sites. Landfill is often simply referred to as deposit.

Material accumulation measures the ‘physical growth of the economy’. Materials are added to the economy’s stock each year (gross additions), and old materials are removed from stock as buildings are demolished, and durable goods disposed of (removals).

Metal ores (also called gross ores) are all the materials which are removed from the mine for the purpose of extracting the desired metal(s). Materials which are removed from the mine for the sole purpose to get access to the reserve, but are then left at the site, are not included.

Non-metallic minerals include sand, gravel, limestone and fertiliser minerals (among others).

Organic materials in nature are composed of carbon-based compounds that have come from the remains of organisms such as plants and animals and their waste products in the environment. Examples include grass, wood, leaves, and manure.

Primary Raw Material is a good sold for production or consumption just as it was found in nature. Examples are crude oil, coal, copper or iron ore, rough diamonds, and agricultural products such as wheat, coffee beans or cotton.

Recycling of waste is defined as any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.

Reuse of waste means any operation by which products or components that are not waste used again for the same purpose for which they were conceived.

Waste means any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force.

References

CCA (Council of Canadian Academies), 2021. Turning Point, Ottawa (ON)

Environment Canada (2019), Canada's 2019 Air Pollutant Emissions Inventory: https://www.canada.ca/en/environment-climate-change/services/pollutants/air-emissions-inventory-overview.html

Eurostat (2018), Circular Material Use Rate-Calculation Method 2018 Edition.

Eurostat (2018-2), Economy-wide material flow accounts HANDBOOK (2018 edition).

Eurostat (2020), Material flows in the circular economy: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Material_flows_in_the_circular_economy

Eurostat (2021), Thematic Glossaries: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Thematic_glossaries

International Resource Panel. (2020), Global Material Flows Database. https://www.resourcepanel.org/global-material-flows-database

Plecher, H. Statista (2020), Canada: real gross domestic product (GDP) growth rate from 2009 to 2021. Statista
https://www.statista.com/statistics/263603/gross-domestic-product-gdp-growth-rate-in-canada/

Watari, T. et al (2019) ‘Total Material Requirement for the Global Energy Transition to 2050: A focus on transport and electricity’, Supplementary Material, *Resources, Conservation & Recycling*, 148, pp. 91-103