

Department of Agricultural and Applied Economics
Established 1909

Taylor Hall
427 Lorch Street
Madison, WI 53707-1503
+1 (608) 262 8966
www.aae.wisc.edu

Sage Model Review Committee
United States Environmental Protection Agency

Thomas F. Rutherford
Optimization Theme
Wisconsin Institutes for Discovery
+1 (608) 316 4362
rutherford@aae.wisc.edu

March 13, 2026

Dear Sir/Madam,

I have been asked to review the SAGE general equilibrium model which has been revised and substantially improved following suggestions made by EPA's Science Advisory Board in 2017. The board recommended that the Agency enhance its regulatory analyses using computable general equilibrium (CGE) models "to offer a more comprehensive assessment of the benefits and costs" of regulatory actions. In response, the EPA has invested in building capacity in this class of economy-wide modeling. A key outcome of this effort is the EPA's CGE model of the U.S. economy, called SAGE. The SAGE model provides an important complement to the analyses typically performed during rule development by evaluating a broader set of economic impacts and offering a more complete estimate of costs.

Among numerous improvements in the models implementation and documentation, the SAGE model has now been recalibrated to the open source state-level dataset produced by the Wisconsin National Data Consortium (WiNDC). WiNDC integrates data from numerous public sources including the Bureau of Economic Analysis, Bureau of Labor Statistics, Energy Information Administration, Federal Reserve, Internal Revenue Service, and the National Bureau of Economic Research. This represents a substantial improvement in transparency and robustness.

The two questions I have been asked to address in my review are:

- i Is the migration of the model to WiNDC operationalized in a transparent and defensible way?
- ii Is the implementation of WiNDC data within SAGE clearly explained in the documentation?

My answer to both of these questions is simply "Yes!". I'm impressed by the GAMS code, the comprehensive documentation, and the care with which the entire package has been produced. In my view, this level of clarity and transparency sets a standard of excellence in analytic tools for policy analysis which exceeds standards represented by many other branches of government, including those which I am most familiar (Department of Energy, the International Trade Commission, and the Department of Agriculture).

While I am enthusiastic about the work product, I maintain some skepticism about the calculation which is used to illustrate how the model might be applied. In my view, the simulation is somewhat mysterious. \$100m in additional labor and capital (\$50m each) is expended comply with an environmental standard. The percentage shock, shared out proportionally across geographies, but the

magnitude of the impact depends on the magnitude and structure of value-added. I guess that the model is being used to evaluate a “general equilibrium multiplier”, but this does not provide a very good illustration of the usefulness of the model itself. I would prefer to use the model to evaluate a specific mitigation policy (e.g. output-based permit allocation, border carbon adjustments, revenue recycling). After going to the trouble of specifying a detailed substitution structure for energy demand, why not demonstrate how this might work in practice?

The most important part of the documentation is the comparison of the WiNDC- and IMPLAN-based models. I hope that this will eventually find a journal output, as the message is important in support of open-source tools.

I think that this comparison could be improved by investigating how the model could be applied for more conventional policy analysis. Years ago John Whalley highlighted three empirical factors which drive economic impacts of policy shocks in applied general equilibrium analysis. These are (in order from most important to least) are (i) tax rates, (ii) elasticities and (iii) benchmark value shares. The choice between WiNDC and IMPLAN are differences in value shares. It is reassuring that the revised source data does not have a first order impact. It would be helpful if the illustrative policy experiment demonstrated this fact.

One aspect of the benchmark value shares which could matter are trade and transport margins. The magnitude of a given change in the price of energy inputs depends on the the elasticity of demand for products (specifically energy). The discussion should distinguish the margin-based formulation from the basic-price model. Again, I would like to see the illustrative calculations investigate these ideas.

Yours sincerely,

A handwritten signature in black ink, appearing to read "Thomas F. Rutherford". The signature is fluid and cursive, with a long horizontal stroke at the end.

Thomas F. Rutherford
Professor

Some Additional Comments regarding Implementation

1. Without being too pendantic, I would suggest that the GAMS keyword “positive variables” could be replaced by “nonnegative variables”.
2. For clarity, Michael Saunders’ capitalization convention would be useful: variables in upper case, sets and parameters in lower case.
3. There is a bug in the assigned value of *non_zeros_before*. This assignment should be:

```
non_zeros_before = card(kd0) + card(res0) + card(id0) + card(ys0) +  
card(cd0) + card(rx0) + card(x0) + card(xn0) + card(xd0) + card(m0) +  
card(nd0) + card(dd0) + card(md0) + card(dm0) + card(nm0) + card(i0) +  
card(g0) + card(ke0) + card(rese0) + card(le0) + card(sav0) +  
card(trn0) + card(ty0) + card(ta0) + card(tm0) + card(tp0) + card(tl0)  
+ card(tfica0) + card(tc0) + card(tk0);
```

4. It has been my experience that if only for the purpose of verifying model logic, GAMS/MPSGE can be used to test model implemented in GAMS/MCP. As an exercise to test my understanding of the model, I was able to implement the SAGE (static) model in MPSGE in a couple of hours. The SAGE . GMS program up the point of benchmark replcation is 2700 lines. My SAGE-MPSGE . GMS program to the same point is 340 lines.

```
$title MPSGE version of Static SAGE Model
```

```
sets
```

```
  s      Sectors /
```

```
    agf      "Agriculture, forestry, fishing and hunting",
    cru      "Crude oil",
    col      "Coal mining",
    min      "Metal ore and nonmetallic mineral mining",
    ele      "Electric power",
    gas      "Natural gas extraction and distribution",
    wsu      "Water, sewage, and other utilities",
    con      "Construction",
    fbm      "Food and beverage manufacturing",
    wpm      "Wood product manufacturing",
    ref      "Petroleum refineries",
    chm      "Chemical manufacturing",
    prm      "Plastics and rubber products manufacturing",
    cem      "Cement manufacturing",
    pmm      "Primary metal manufacturing",
    fmm      "Fabricated metal product manufacturing",
    cpu      "Electronics and technology manufacturing",
    tem      "Transportation equipment manufacturing",
    bom      "Other manufacturing",
    trn      "Transportation",
    ttn      "Truck transportation",
    srv      "Services",
    hlt      "Healthcare services" /,
```

```
  r      Regions /
```

```
    nor      "Northeast",
    sou      "South",
    mid      "Midwest",
    wes      "West" /,
```

```
  h      Households (quintiles) /hh1*hh5/
```

```
  mrg  Margin types /
```

```
    trn      Transport
    trd      Trade /,
```

```
  trn  Transfer types /
```

```
    hucval    "Unemployment compensation",
    hwcval    "Workers compensation",
    hssval    "Social security",
    hssival   "Supplemental security",
    hpawval   "Public assistance or welfare",
    hvetval   "Veterans benefits",
    hsurval   "Survivors income",
    hdisval   "Disability",
    hedval    "Educational assistance",
    hcspval   "Child support",
    hfinval   "Financial assistance",
    medicare  "Medicare",
    medicaid "Medicaid",
    other     "Other" /;
```

```
alias  (s,g,ss), (r,rr), (h,hh), (mrg,m);
```

```

parameters
    ys0(r,s,ss)      Benchmark sectoral output (sector by commodity)
    ld0(r,s)         Benchmark labor demand
    kd0(r,s)         Benchmark capital demand
    res0(r,s)        Benchmark fixed factor resource
    id0(r,ss,s)      Benchmark intermediate demand
    ty0(r,s)         Benchmark tax rate - output
    tk0(r)           Benchmark tax rate - capital income tax
    tp0(r)           Benchmark tax rate - payroll
    cd0(r,s,h)       Benchmark consumer demand
    dcd0(r,s,h)      Benchmark - discretionary demands
    scd0(r,s,h)      Benchmark - subsistence demands (non-discretionary)
    tc0(r)           Tax rate - consumption
    xr0(r,s)         Benchmark regional supply
    xn0(r,s)         Benchmark intranational exports
    x0(r,s)          Benchmark international exports
    a0(r,s)          Benchmark Armington aggregate
    ta0(r,s)         Benchmark tax rate - intermediate demand
    nd0(r,s)         Benchmark intranational imports
    dr0(r,s)         Benchmark regional demand
    m0(r,s)          Benchmark international imports
    tm0(r,s)         Benchmark import tariff
    md0(r,mrg,s)     Benchmark total margin demand
    nm0(r,s,mrg)     Benchmark margin supply from national market
    dm0(r,s,mrg)     Benchmark margin supply from local market
    trn0(r,h)        Benchmark household transfer payments
    hhtn0(r,h,trn)   Benchmark disaggregated transfer payments
    sav0(r,h)        Benchmark household investment
    le0(r,rr,h)      Benchmark labor endowment
    rese0(r,s,h)     Benchmark resource income
    ke0(r,h)         Benchmark capital rental income
    i0(r,s)          Benchmark investment demand
    g0(r,s)          Benchmark government demand
    tl_avg0(r,h)     Benchmark labor income tax
    tfica0(r,h)      Benchmark FICA tax rate;

$if not set benchmark_file $set benchmark_file "../data/default_aggregation.gdx"

$gdxin %benchmark_file%
$load ys0 ld0 kd0 res0 id0 ty0 tk0 tp0 cd0 scd0 xr0=xd0 xn0 x0 a0 ta0
$load nd0 dr0=dd0 m0 tm0 md0 nm0 dm0 trn0 sav0 le0 rese0 ke0 i0 g0 hhtn0 tl_avg0 tfica0 tc0

parameters
    se_klem(s)       ESUB : materials and value-added-energy bundle
    se_kl(s)         ESUB : value-added
    se_kle(s)        ESUB : value-added-energy bundle
    se_ene(s)        ESUB : electricity and primary energy bundle
    se_en(s)         ESUB : primary energy bundle

    se_dn(s)         ESUB : domestic-national armington elasticity
    se_nf(s)         ESUB : national-foreign armington elasticity
    se_cl(r,h)       ESUB : consumption-leisure bundle
    se_inv           ESUB : investment bundle

    te_dx(s)         ETA : domestic and exported production
    te_k_ex          ETA : sector differentiated extant capital
    eps_ex           demand elasticity - exports
    eps_im           supply elasticity - imports
    re(s)            resource elasticity - fixed factor availability

```

```

        delta          Depreciation rate,
        rbar           Benchmark interest rate,
        se_res_lr(s)   Long run supply elasticity,
        eta(r,h)       ESUB : inverse of consumption over time
        lse_inc        Labor supply elasticity -- income,
        lse_sub        Labor supply elasticity -- substitution;

$include ../data/parameters

parameter          tl(r,h)          Applied wage income tax,
                  tl0(r,h)          Benchmark income tax;

tl(r,h) = tl_avg0(r,h)+tfica0(r,h);
tl0(r,h) = tl(r,h);

parameter          vb(r,h)          Foreign transfers;
vb(r,h) = sav0(r,h) + sum(g,cd0(r,g,h))
        - trn0(r,h)
        - sum(rr, le0(rr,r,h)*(1-tl0(r,h)))
        - sum(s, rese0(r,s,h))
        - ke0(r,h);

display vb;

parameter          y0(r,s) Sectoral supply;
y0(r,s) = sum(g,ys0(r,s,g));

*      Labor-leisure choice:

parameter
    l0(r,h)          benchmark - household labor supply
    leis0(r,h)        benchmark - leisure
    dc0(r,h)          benchmark - discretionary consumption bundle
    cl0(r,h)          benchmark - consumption(c)-leisure(l) bundle;

* household labor income
l0(r,h)              = sum(rr, le0(r,rr,h));
leis0(r,h)           = -lse_inc * l0(r,h) ;

* initialize discretionary component of final demand
dcd0(r,s,h)          = cd0(r,s,h)-scd0(r,s,h);

* discretionary commodity bundles for utility functions (discretionary spending)
dc0(r,h)              = sum(s, dcd0(r,s,h))*(1+tc0(r));

* compute benchmark leisure and the c-l substitution elasticity
cl0(r,h)              = dc0(r,h)+(1-tl0(r,h)-tfica0(r,h))*leis0(r,h);

se_cl(r,h) = lse_sub * cl0(r,h)/dc0(r,h) * l0(r,h)/leis0(r,h);
display se_cl;

leis0(r,h) = leis0(r,h) * (1-tl(r,h));

parameter          tax0          Benchmark tax revenue;
tax0 =             sum((rr,r,h),le0(rr,r,h)*tl0(r,h))
        + sum((r,s),y0(r,s)*ty0(r,s))
        + sum((r,s),ld0(r,s)*tp0(r))
        + sum((r,h),dc0(r,h)*tc0(r))
        + sum((r,s),(res0(r,s)+kd0(r,s))*tk0(r))
        + sum((r,g),a0(r,g)*ta0(r,g))
        + sum((r,g),m0(r,g)*tm0(r,g));

```

```

parameter          vbgovt          Government transfers;
vbgovt = sum((r,g),g0(r,g)) + sum((r,h),trn0(r,h)) - tax0;

parameter          vbchk;
vbchk = sum((r,g),x0(r,g)-m0(r,g)) + vbgovt + sum((r,h),vb(r,h));
display vbchk;

parameter          vbratio(r,h)    Foreign transfer fraction of consumption;
vbratio(r,h) = vb(r,h)/sum(g,cd0(r,g,h));
display vbratio;

parameter          eta_s(s)        Elasticity of supply /
                                min 1, agf 2, cru 0.5, col 1, gas 0.5/;

parameter          tp(r)           Payroll tax,
                                tk(r)           Capital tax,
                                ta(r,g)         Sales tax,
                                tm(r,g)         Import tariff,
                                ty(r,s)         Production tax-subsidy,
                                ms0(r,mrg)      Margin supply;

tp(r) = tp0(r);
tk(r) = tk0(r);
ta(r,g) = ta0(r,g);
tm(r,g) = tm0(r,g);
ty(r,s) = ty0(r,s);
ms0(r,mrg) = sum(g,md0(r,mrg,g));

*          Sets required for nesting assignments in prod:Y

sets          sm(s)    Materials sectors (non-energy)
              sen(s)   Primary energy sectors / col, gas, ref /,
              sel(s)   Electricity sector / ele /;

sm(s) = s(s)$(not (sen(s) or sel(s)));

parameter          se_rklem(r,s)    ESUB: r-klem bundle in resource extraction sectors;
se_rklem(r,s) = se_res_lr(s) * res0(r,s)/(y0(r,s)-res0(r,s));

parameter          xd0(g)           Export demand (aggregate);
xd0(g) = sum(r,x0(r,g));

```

```

$ontext
$model:SAGE

$sectors:
    Y(r,s)      !      Production
    X(r,g)      !      Supply
    A(r,g)      !      Absorption
    MS(r,mrg)   !      Margin supply
    C(r,h)      !      Discretionary consumption

$commodities:
    PA(r,g)     !      Armington composite price
    PN(g)       !      National market
    PY(r,s)     !      Industry supply priceo
    PC(r,h)     !      Consumption price index
    PM(r,mrg)   !      Price of margins,
    PD(r,g)     !      Local market
    PX(g)       !      Export market
    PL(r)       !      Wage rate
    PK(r)       !      Capital price
    PR(r,s)$res0(r,s) ! Resource price
    PKE        !      Capital income
    PTAX        !      Tax revenue
    PFX        !      Foreign exchange

$consumers:
    RH(r,h)     !      Representative household
    GOVT        !      Government
    NYSE        !      Capital earnings agent
    INV         !      Investment agent
    IRS         !      Tax revenue agent
    EXP         !      Export demand agent

$auxiliary:
    XD(g)$xd0(g) !      Export demand

$prod:Y(r,s)  s:se_rklem(r,s)
+             klem:se_klem(s)
+             mat(klem):0
+             kle(klem):se_kle(s)
+             e(kle):1
+             pe(e):se_en(s)
+             kl(kle):se_kl(s)
    o:PY(r,s)  q:y0(r,s)      A:IRS   t:ty(r,s)
    i:PA(r,g)  q:id0(r,g,s)   mat:$sm(g) e:$sel(g) pe:$sen(g)
    i:PL(r)    q:ld0(r,s)     A:IRS   t:tp(r) p:(1+tp0(r)) kl:
    i:PK(r)    q:kd0(r,s)     A:IRS   t:tk(r) p:(1+tk0(r)) kl:
    i:PR(r,s)  q:res0(r,s)    A:IRS   t:tk(r) p:(1+tk0(r))

$prod:X(r,g)  t:te_dx(g)  s:1
    o:PN(g)    q:xn0(r,g)
    o:PX(g)    q:x0(r,g)
    o:PD(r,g)  q:xr0(r,g)
    i:PY(r,s)  q:ys0(r,s,g)

```

```

$prod:A(r,g)      s:0
+                m:se_nf(g)
+                dn(m):se_dn(g)
                o:PA(r,g)      q:a0(r,g)      A:IRS t:ta(r,g)
                i:PM(r,mrg)    q:md0(r,mrg,g)
                i:PN(g)        q:nd0(r,g)      dn:
                i:PD(r,g)      q:dr0(r,g)      dn:
                i:PFX          q:m0(r,g)      A:IRS t:tm(r,g) p:(1+tm0(r,g)) m:

$prod:MS(r,mrg)   s:1
                o:PM(r,mrg)    q:ms0(r,mrg)
                i:PN(g)        q:nm0(r,g,mrg)
                i:PD(r,g)      q:dm0(r,g,mrg)

$prod:C(r,h)
                o:PC(r,h)      q:dc0(r,h)
                i:PA(r,g)      q:dcd0(r,g,h)  a:IRS t:tc0(r)

$demand:RH(r,h)   s:se_cl(r,h) c:1
                d:PC(r,h)      q:dc0(r,h)
                d:PL(r)        q:leis0(r,h)
                e:PA(r,g)      q:(-scd0(r,g,h))
                e:PFX          q:(trn0(r,h)-sav0(r,h)+vb(r,h))
                e:PL(rr)       q:(leis0(r,h)$sameas(r,rr)+le0(rr,r,h)*(1-tl(r,h)))
                e:PR(r,s)      q:rese0(r,s,h)
                e:PKE          q:ke0(r,h)

$demand:GOVT
                d:PA(r,g)      q:g0(r,g)
                e:PFX          q:(-sum((r,h),trn0(r,h)))
                e:PTAX         q:tax0
                e:PFX          q:vbgovt

$demand:IRS
                d:PTAX
                e:PL(rr)       q:(sum((r,h),le0(rr,r,h)*tl(r,h)))

$demand:NYSE
                d:PKE
                e:PK(r)        q:(sum(s,kd0(r,s)))

$demand:INV s:0
                d:PA(r,s)      q:i0(r,s)
                e:PFX          q:(sum((r,h),sav0(r,h)))

$demand:EXP
                e:PFX          q:(2*sum(g,xd0(g)))
                e:PX(g)$xd0(g) q:(-xd0(g))      r:XD(g)
                d:PFX

$constraint:XD(g)$xd0(g)
                XD(g) =e= (PX(g)/PFX)**eps_ex(g);

$offtext
$sysinclude mpsgeset SAGE

XD.L(g) = 1$xd0(g);

SAGE.iterlim = 0;
$include SAGE.GEN
solve SAGE using mcp;

```

5. One attraction of the MPSGE formulation is that it would be a fairly simple matter to implement the model in Julia/Jump using Mitch Phillipson's MPSGE.jl package which would provide a fully open source version of SAGE. (<https://windc.wisc.edu/posts/?tag=julia>).