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Abstract

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The paper presents an applied dynamic general equilibrium model of the Norwegian economy. The model distinguishes between a large exposed industry that faces exogenous world market prices, five smaller sheltered industries and the public sector. There are installation costs of investment in the exposed industry. On the household side, a representative consumer with infinite horizon allocates expenditure between different periods, and splits expenditure on leisure and consumer goods in any one period.

A particular feature of the model is a two-way link between the environment and the economy. The environment affects the economy in the areas of productivity, depreciation and household welfare.

The paper discusses the nature of environmental feedbacks to include in an applied dynamic general equilibrium model, and studies the workings of the model in a simplified version. A substantial appendix presents the equation system of the model.

Keywords: Environment, Environmental economics, Growth model, Economics

Contents

1 Introduction*

This paper presents a computable dynamic general equilibrium (CGE) model of Norway. A particular feature of the model is a two-way link between the environment and the economy. We model a small open economy facing exogenous product prices and an exogenous interest rate. On the production side, a large competitive industry produces a good for export and domestic absorption. Producers have perfect foresight. The competitive industry faces installation costs of investment. Five smaller industries produce sheltered goods. Inputs to the public sector are exogenous.

On the consumption side an infinitely lived consumer allocates expenditure to different periods by means of an additively separable intertemporal utility function. In any one period, the consumer allocates expenditure between leisure and consumption. The consumer has perfect foresight.

The model tracks emissions to air and traffic volumes. A set of detailed emission coefficients links emissions to material inputs, heating oil and gasoline consumption. Traffic volumes depend on gasoline and auto-diesel consumption. The emissions to air and the traffic volumes are the links or feedbacks from the economy to the environment.

We model three feedbacks from the environment to the economy. One is a feedback from the environment directly to the welfare of the consumer. Examples are annoying noise from traffic, reduced air quality and reduced recreational value of freshwater lakes because of acid rain.

A second feedback is an effect on labour productivity. We argue that noise, traffic accidents and reduced air quality will increase sick leaves and reduce labour productivity in other ways (disabilities, tiredness etc.). These effects are different from (though they in practice may be difficult to separate from) the welfare aspects of noise, traffic accidents and reduced air quality.

The third feedback is a link from environmental quality to the rate of capital depreciation. This feedback has two motivations. One is the increase in corrosion caused by sulphur emissions in particular. Another is the impact of traffic on road depreciation. Heavy traffic wears down the roads and increases the need for road maintenance.

The model gives a rough indication of important environmental effects of economic policy. Its merit is the general equilibrium perspective on the link between the economy and the environment.

A dynamic growth model with environmental feedbacks is useful for many purposes. First, it will in principle improve the description of the process of economic growth and represent a step towards realism. Second, it shows that growth in GDP or consumption is not equivalent to growth in welfare because of the effect from the environment to the welfare of the consumer. Third, it contributes to the debate on how much growth is compatible with a sustainable development. Fourth, it invites a study of how one can use taxes, subsidies and other regulations to improve welfare, and whether consumption and GDP temporarily fall in the process. Other topics include policies to stimulate growth, the costs and benefits of environmental regulation, the impact of public consumption on the environment, and many other issues in the intersection between economic growth and the environment.

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In the literature on economic growth with environmental feedbacks, Van der Ploeg and Withagen (1991) analyse a specific analytical model where emissions are proportional to production, and (direct) utility is additive in stock and flow emissions. In Tahvonen and Kuuluvainen (1993), emissions are inputs to production and stock emissions affect utility and production of a renewable resource. Gradus and Smulders (1993) study the consequences of adverse effects of emissions on health and productivity in the Lucas (1988) model of human capital accumulation. The present model includes several of the features discussed in these papers.

In the applied literature Nordhaus (1993) presents a global growth model in which production emits CO_2. CO_2 emissions increase the temperature of the earth, which harms production. Feedbacks of a similar kind are modelled by Kverndokk (1993) in a model without capital accumulation. Our model distinguishes itself from these efforts by its single-country perspective and a focus on different environmental feedbacks. The study by Glomsrød, Vennemo and Johnsen (1992) includes most of the environmental feedbacks of the present model, but they are modelled as unidirectional effects. Brendemoen and Vennemo (1994) take that methodology further. There is a large literature on models that track emissions from economic activity. A good example is Jorgenson and Wilcoxen (1993), who survey some of their own work and that of others.

The paper is organized as follows: Section 2 discusses our modelling approach to environmental feedbacks. Section 3 outlines the principles of our model. Appendix A gives the full set of equations. Appendix B describes the basis for the user cost of capital formulas used in the model. Appendix C describes the sets of commodities and activities used in the model.

2 Important environmental feedbacks

Several authors value environmental goods in Norway, see the survey of Navrud and Strand (1992). Many studies concern phenomena that have small links to the national economy, because they are small compared with the national economy, or their relation to underlying economic variables is unclear. The best feedbacks to include in a CGE model are easily linked to economic variables of the model, and have a non negligible national importance.

The environmental feedbacks of this model are based on on the model of environmental effects of macroeconomic policy developed by Brendemoen, Glomsrød and Aaserud (1992)[1] and the model of traffic accidents and the economy in Glomsrød, Nesbakken and Aaserud (1994). Brendemoen, Glomsrød and Aaserud (1992) focus on 11 external effects of economic activity, namely acidification of lakes, acidification of forests, health damages and annoyance from emissions of NO_x, SO_2, CO and particulates, corrosion, noise, traffic accidents, congestion and road depreciation. Lack of data makes the exact size of an effect difficult to assess. Therefore their results, as well as those of Glomsrød, Nesbakken and Aaserud (1994) serve as illustrations and not precise estimates of environmental externalities.

Road depreciation is a side effect of driving, especially in the wintertime. Studded tires are deemed necessary in Norway because of the harsh climate. The tires tear up the road surface. Brendemoen, Glomsrød and Aaserud (1992) assume the effect of traffic on road depreciation to be proportional in the relevant range to consumption of auto-diesel and gasoline. A linear model is however not reasonable because it implies more than 100 per cent depreciation for

[1]This paper is in Norwegian. Alfsen, Brendemoen and Glomsrød (1992) or Brendemoen and Vennemo (1993) are English papers with similar material.

some (large) level of traffic. To avoid this problem, the present model says that the marginal effect on depreciation decreases to zero when traffic suffocates the roads. The maximum is set to three times the present rate of road depreciation.

We assume a monotonously decreasing effect. This is probably not correct. Heavier traffic will imply more stop-go driving, which probably increases road depreciation more than proportionally over some range. If fuel efficiency increases over time, traffic and road depreciation will increase more than proportionally with gasoline and auto-diesel consumption. As we have no data on these relationships, we assume the monotonously decreasing effect for simplicity.

Tearing up the surface contributes to emissions of particulates, which may harm health. The model does not include this effect for data reasons.

Corrosion increases the capital costs of private producers. We treat it as an increase in capital depreciation of private producers. Corrosion is specified as a function of SO_2 emissions for data reasons. In reality, pollutants like NO_x, also contribute to corrosion. As for road depreciation, We assume SO_2 emissions to have a decreasing partial effect, reaching zero when the rate of capital depreciaton is three times the base year rate. The model distinguishes between different capital goods (see appendix C). The data on corrosion is limited to its effect on the category "buildings" (which also includes other structures). We assume the effect on other capital goods to be zero.

Corrosion may also affect the economy through decreased value of the culturally valuable buildings and structures. This effect is not included in the model due to data limitations.

When sport fishing is free, *acidification of lakes* influences the consumer but not the producer, i.e. it is a consumer externality. It is a producer externality when it affects owners of commercial sport fishing rights. The model has no production function for sport fishing and we treat acidification of lakes as a consumer externality. Acidification of lakes is assumed to be proportional to emissions of SO_2 and NO_x.

Acidification of forests leads to decreased growth in forests (about two-thirds of the estimated cost) and reduced recreational value (about one-third of the estimated cost). The reduced forest growth represents a loss of income for owners of the forests, but it doesn't affect current sales. It decreases the return to a particular capital good. As a loss in income it is similar to other income losses that reduce consumer welfare. Reduced recreational value of forests obviously reduces consumer welfare. Acidification of forests is assumed to be proportional to emissions of SO_2 and NO_x.

Noise annoys the public and affects the productivity of workers who are disturbed in their sleep or must work in a very noisy environment. Businesses spend money to isolate windows and other parts of their buildings from noise to boost productivity and to give non pecuniary benefits to its workforce. One half of the estimate of the cost of noise of Brendemoen, Glomsrød and Aaserud (1992) reflects productivity loss. The rest reflects the consumer's value of distress from noise. We have data from noise from traffic. We assume the welfare cost of noise to be proportional to traffic as measured by gasoline and auto-diesel consumption.

The productivity part has a max of around one per cent productivity loss, which is an educated guess of the maximum damage from noise to productivity.

Health damages affect the quality and quantity of labour supply. Reduced health forces the worker to more sick leaves and to lower productivity. For simplicity we subsume both in the quality indicator. Brendemoen, Glomsrød and Aaserud (1992) assume emissions and health damage to be proportional. We assume a maximum productivity loss of 3 per cent each from emissions of NO_x and particulates, and 1.5 per cent each from emissions of SO_2 and CO. This guess is based on the relative damage estimates of emissions in Brendemoen, Glomrød and Aaserud (1992). For simplicity we let the marginal impact on productivity decrease monotonously as the quality of the air gets worse.

Besides the productivity aspect, an increased risk of illness or death affects consumer welfare. Both workers and nonworkers are at risk. Some of the most vulnerable groups are nonworkers, i.e. children and the elderly. We have no data for the welfare aspect of reduced health. Somewhat arbitrarily we claim the welfare cost to be one half the productivity cost.

Traffic accidents and *congestion* affect consumer welfare when consumers drive in their leisure time (including the time back and forth to work). They affect producers when they hurt professional transport activities. At present, our data do not distinguish between the two. Our production structure does not let us model traffic accidents and congestion as producer externalities in a satisfactory way. We treat them as pure consumer externalities. In this way the resources that producers divert from productive activities due to accidents and congestion, which in a proper model should have reached consumers as lower consumption, instead reach consumers as an externality outside the market.

A traffic accident may change the labour supply and productivity of those that are hurt, and traffic accidents will kill people. Similarly to the analysis of Glomrød, Nesbakken and Aaserud (1994), we construct a measure of the productivity loss from traffic accidents based on data for temporary illness and chronic disabilities. A chronic disability lasts 37 years, which is the average remaining life-length of those permanently injured. Similarly, a death counts as a reduction in the population for 37 years. Glomsrød, Nesbakken and Aaserud (1994) include a link from traffic accidents to public expenditures on health care which we leave out here because of problems of aggregation. The estimate from Brendemoen, Glomsrød and Aaserud (1992) of the welfare cost of traffic accidents is reduced 20 per cent to avoid double counting.

Traffic accidents and congestion are linked to the level of traffic. We measure traffic by gasoline and auto-diesel consumption. Accidents and congestion are open to other solutions than reduced traffic. Increased road capacity can reduce congestion. Experience suggests, however, that increased road capacity also induce new demand as congestion is part of the perceived cost of private driving. Omitting road capacity from both sides of the equation gives the simpler solution that we have chosen. Toll roads and other payment schemes may also reduce congestion. The effects of such schemes are not modelled.

The question arises of whether the effects on consumer welfare influence consumer behaviour. More specifically the issue is whether the saving decision or the labour supply decisions of the consumer are affected, as these are the actions the consumer makes in the model. Environmental quality obviously affects consumer decisions at the micro level. Acidification of forests and lakes may reduce the demand for fishing rods and hiking boots and increase the demand for charter-tours to foreign countries. Morbidity from air pollution may increase the demand for everything from medicines to countryside houses. This will have repercussions on the demand for other goods through the budget constraint. It is unlikely that the effect on savings will be zero. There is however no particular reason to suspect environmental quality to increase (rather than decrease) savings. Therefore, we disregard any effect on savings.

The labour supply decision may be more prone to influence from environmental quality (and we have argued in that direction above). But if illness forces a person to work less, it is perhaps an improper use of terms to claim that the reason is "increased preference" for leisure. A possible alternative could be to say that her time endowment decreases. That is not quite to the point either. A person with a serious illness has the same amount of time on her hands as others. We have chosen the productivity interpretation described above as our alternative.

Some outside observers will perhaps find the list of feedback effects in the model scant. Where are the "big issues" that lead environmentalists to advocate a profound change in our system of production? The answer is that big issues like the greenhouse effect, loss of biodiversity, deforestation, soil degradation etc. are *global* problems that are affected by, and affect the *global* economy. The effect of Norwegian economic activity on these problems can be neglected. We cannot model a two-way interaction between the Norwegian economy and global problems. The model will pick up effects going from the global environment as changes in relative world market prices and productivity growth rates. Imported pollution may also hurt Norwegian consumers in the form of further increases in acidification of forests and lakes, for example. Since imported pollution does not change because of Norwegian actions, such damage is a constant in the utility function that amounts to a different scaling of utility.

3 A simplified model

This section presents a simplified model that conveys the essence of the full CGE model. The public sector and sheltered sectors are ignored. Functional forms are for the most part not specified. The model consists of an "ordinary" static model, environmental feedbacks in the model and and a dynamic model. No time subscript means (end of) "this period", and subscripts -1 or $+1$ mean "previous period" and "next period" respectively.

The static model

$$
\begin{aligned}
p &= B(p_l, p_e, p_f, p_k, p) && (1)\\
B_1'X &= L && (2)\\
B_2'X &= E && (3)\\
B_3'X &= F && (4)\\
B_4'X &= K && (5)\\
B_5'X &= M && (6)\\
P &= P(p_l h, p) && (7)\\
L &= (1+n)^t(Th(1+g)^t - hP_1'H) && (8)\\
C &= (1+n)^t P_2'H && (9)\\
J &= (1+\delta)K - K_{-1} && (10)\\
Z - Z_{-1} &= iZ_{-1} + pX - pM - pJ(1+G) - pC + p_f(\bar{F} - F) + p_e(\bar{E} - E) && (11)\\
G &= G(J/K) && (12)
\end{aligned}
$$

Environmental feedbacks

$$
\begin{aligned}
h &= h(F_t) \qquad h' < 0 \qquad \lim_{t\to\infty} h(F_t) = \bar{h} && (13)\\
\delta &= \delta(F_t) \qquad \delta' > 0 \qquad \lim_{t\to\infty} \delta(F_t) = \bar{\delta} && (14)\\
U &= \frac{\mathcal{P}_0}{\mathcal{P}} W_{-1} - \mathcal{D} && (15)
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{P}_0 &= \left[\sum_{t=0}^{\infty} \left(\frac{1+n}{1+\rho}\right)^t \left[\frac{(1+\rho)^t}{(1+i)^{t+1}} P_{0t}\right]^{(\sigma-1)/\sigma}\right]^{\frac{\sigma}{\sigma-1}} \\
\mathcal{P} &= \left[\sum_{t=0}^{\infty} \left(\frac{1+n}{1+\rho}\right)^t \left[\frac{(1+\rho)^t}{(1+i)^{t+1}} P_t\right]^{(\sigma-1)/\sigma}\right]^{\frac{\sigma}{\sigma-1}} \\
W_{-1} &= \sum_{t=0}^{\infty} \frac{(1+n)^t}{(1+i)^{t+1}} P_t H_t
\end{aligned}
$$

$$
\mathcal{D} = \frac{\mathcal{P}_0}{\mathcal{P}} D - D_0 \tag{16}
$$

$$
\begin{aligned}
D_0 &= \sum_{t=0}^{\infty} \frac{(1+n)^t}{(1+i)^{t+1}} P_{0t} a F_{0t} \\
D &= \sum_{t=0}^{\infty} \frac{(1+n)^t}{(1+i)^{t+1}} P_t a F_t
\end{aligned}
$$

Dynamic model

$$
p_k = \frac{q}{1+i}\left(i + \delta(1+i) - \frac{(q_{+1} - q)}{q}\right) - p\left(\frac{J}{K}\right)^2 G' \tag{17}
$$

$$
q = (1 + G + \frac{J}{K} G')p \tag{18}
$$

$$
H = \mu\left(\frac{1+\rho}{1+i}\right)^{-t/\sigma} P_t^{-1/\sigma} \tag{19}
$$

$$
\lim_{t\to\infty} Z_t(1+i)^{-t} = 0 \tag{20}
$$

Symbols

- a: damage parameter in disutility functions
- C: consumption
- D: value of negative externalities
- D: value of negative externalities, baseline scenario
- $\mathcal{D}$: disutility of negative externalities
- E: hydroelectric power consumption
- $\bar{E}$: exogenous hydroelectric power production
- F: fuel oil consumption
- $\bar{F}$: exogenous fuel oil production
- G: installation costs
- g: exogenous productivity increase
- H: full consumption
- h: health induced productivity index

- i: interest rate
- J: gross investment in real capital
- K: capital stock
- L: employment (in efficiency units)
- M: material input consumption
- n: population growth rate
- P: price index of full consumption
- $\mathcal{P}$: intertemporal price index of wealth
- $\mathcal{P}_0$: intertemporal price index of wealth, baseline scenario
- p: output price, price of consumption, investment and material inputs, numeraire
- p_e: price of hydroelectric power
- p_f: price of fuel oil
- p_k: price of capital
- p_l: price of labor (in efficiency units)
- q: shadow price of investments
- T: time endowment
- U: index of intertemporal utility
- W_1: household wealth
- X: gross production
- Z: value of foreign assets
- δ: capital depreciation rate
- μ: parameter inversely related to marginal utility of wealth
- ρ: subjective rate of time preference
- σ: inverse of intertemporal elasticity of substitution

Equations (1) to (12) constitute a standard static model of a small open economy. Equation (1) requires that the output price of the competitive good, which is the numeraire, equals unit costs. The function $B()$ is the unit cost function. The five input factors are labor (in efficiency units), capital, fuel, hydroelectric power and material inputs. Fuel and hydroelectric power are included to facilitate analyses of energy and the environment. All electricity is hydroelectric in Norway. The price of material inputs equals the output price, as materials are produced goods.

Equations (2) to (6) use Shepard's lemma to derive the factor demands.

Equation (7) defines the price index P of full consumption (the consumption good and leisure) H. We assume homothetic intratemporal utility, in which case the expenditure function is written PH. The price index is in other words well defined as a cost-of-living index for constant full consumption (which is a utility indicator). Consumers do not consume energy in this simple exposition and energy prices are not arguments in P. In the full model, household consumption of energy is proportional to household consumption in general.

This paper follows the standard practice (see, e.g., Jorgenson and Yun (1986, 1990)) of assuming technical progress in utility. Leisure generates more and more (marginal) utility over time, and the willingness to pay for leisure increases. Just like the producer is willing to purchase a constant amount of labor at an increasing wage, the consumer is willing to purchase a constant amount of leisure at an increasing wage. Except for very restrictive utility functions, an assumption like this is necessary to avoid corner solutions for labor supply when the model includes steady state income growth (King, Plosser and Rebelo, 1988).

The first argument of the price index is then explained the following way: We start with the wage rate, which is the price in efficiency units (p_l), times the number of efficiency units at time t, $((1+g)^t h)$. g is the rate of labor augmenting technical progress. h reduces the productivity level due to respiratory illnesses etc. For given p_l and h, the wage rate will increase by g each year. The marginal utility of leisure will also increase by g, however. The price of leisure that influences decisions is therefore $p_l h$, which is the first argument of the price index P. The second argument is the price of the consumption good. Consumption is a produced good and its price equals the numeraire.

Equation (8) gives the labor supply in efficiency units as the labor supply of each individual $(Th(1+g)^t - hP_1'H)$ times the number of individuals at time t, $(1+n)^t$. The labor supply of each individual is the time endowment in efficiency units $(Th(1+g)^t)$ less the demand for leisure in efficiency units $(hP_1'H)$. H is per capita full consumption. Shephard's lemma is invoked to calculate the demand for leisure.

Equation (9) gives the consumer good demand as the number of individuals times the individual consumer good demand. Again, the individual demand is derived using Shephard's lemma.

Equation (10) is the capital accumulation equation. J is gross investment. We assume exponential decay. Depreciation occurs instantly by a Standard for National Accounts convention.

Equation (11) is the current account. The current account equals production $(pX + p_f\bar{F} + p_e\bar{E})$ less total demand $(pM + pJ(1+G) + pC + p_fF + p_eE)$, which is the trade surplus, pluss capital income from abroad (iZ_{-1}). Norway exports both petroleum and electricity.

Equation (12) defines the installation cost function as a function of the gross investment ratio as suggested by, e.g., Summers (1981). A growth model with installation costs were first analyzed by Abel and Blanchard (1983). Blanchard and Fischer (1989), chapter 2 discusses an open economy version of such a model.

For given values of K, K_{-1}, Z, Z_{-1}, h, δ, g, p_e, p_f, $\bar{F}$ and $\bar{E}$, the model (1) to (12) solves for L, E, F, M, X, H, C, J, p_l, p_k, P and G. Equations (1) to (12) in other words solve for production and consumption flows in terms of exogenous factor supplies, just like an ordinary static general equilibrium model.

Equations (13) to (15) specify the environmental feedbacks to the model. The feedbacks are discussed in some detail in section 2, and we just note how they fit into the general picture. Health damage and depreciation (equations (13) and (14)) are functions of emissions to air and gasoline and autodiesel consumption in the full model, but the emissions are almost proportional to fuel oil consumption (gasoline and autodiesel are examples of fuel oil consumption). That is why the functions have fuel oil consumption as their argument.

Equation (15) is the intertemporal money metric indirect utility function of the consumer. The first term is the money metric indirect utility function for a given level of the environmental feedback $\mathcal{D}$. This term is the outcome of maximizing a CES-utility function $\sum_t(1+n)^t(1+\rho)^{-t}H_t^{1-\sigma}$ subject to the intertemporal budget constraint $\sum_t(1+n)^t(1+i)^{-(t+1)}P_tH_t = W_{-1}$, where W_{-1} is initial wealth.

The second term is the external environmental feedback. The feedback is described in more detail in equation (16). D_0 is the reference impact of externalities, similarly to $\mathcal{P}_0$ in equation (15). It normalizes the baseline utility level (ie. the one corresponding to $P_t = P_{0t}$, $F_t = F_{0t}\ \forall t$) to baseline wealth at time 0, W_{-1}^0. The disutility of an externality is proportional to fuel oil consumption because the externalities are proportional to fuel oil consumption.

Our specification of utility meets the assumption that the feedbacks do not alter savings or labor supply behavior. The specification assumes that the marginal value of an externality (in terms of full consumption at the same time) stays constant over time.

With equations (13) to (15), the model is a static model with environmental feedbacks. It gives the "short run" or temporary equilibrium solution.

The objective of the (forward-looking) dynamic part of the model is to explain the path of the state variables K and Z over time. This will yield the "long run" or time path solution of the model. We recall that K is capital and Z is the value of net foreign assets abroad. Equations (17) and (18) focus on the accumulation of capital. Equation (17) gives the user cost of capital in a perfect forsight economy with installation costs. Equation (18) defines the shadow cost of capital, q, in terms of the installation cost function. Capital accumulation is linked forward in time through the term q_{+1} in equation (17).

To reach equations (17) and (18), we ask how an owner/manager should accumulate capital over time in order to maximize the value of the firm. Since the financing of investments does not matter for the value of the firm when there are no taxes, we may without loss of generality assume investments to be financed by retained earnings in this exposition. Let $\mathcal{F}_t(K_t)$ be the restricted profit function of the firm. The present value of the firm is $\sum_{t=0}^{\infty}\left(\mathcal{F}_t(K_t) - p_tJ_t(1+G(J_t/K_t))\right)\left(\frac{1}{1+i}\right)^{t+1}$. The equation for accumulation of capital is $J_t = (1+\delta)K_t - K_{t-1}$. The problem of the owner is to maximize the value of the firm subject to the capital accumulation constraint:

$$\max_{\{K_t J_t\}} \mathcal{L} = \sum_{t=0}^{\infty}\left(\mathcal{F}_t(K_t) - p_tJ_t(1+G(J_t/K_t))\right)\left(\frac{1}{1+i}\right)^{t+1} - \sum_{t=0}^{\infty}\lambda_t((1+\delta)K_t - K_{t-1} - J_t) \quad (21)$$

The first order conditions of the problem are

$$\frac{\partial \mathcal{L}}{\partial K_t} = \left(\frac{1}{1+i}\right)^{t+1}\left[\mathcal{F}_{tK'} + p_t(\frac{J_t}{K_t})^2G'\right] - (1+\delta)\lambda_t + \lambda_{t+1} = 0 \qquad \forall t \geq 0 \quad (22)$$

$$\frac{\partial \mathcal{L}}{\partial J_t} = -\left(\frac{1}{1+i}\right)^{t+1} q_t + \lambda_t = 0 \qquad \forall t \geq 0 \quad (23)$$

where $q = p(1 + G + \frac{J}{K}G')^2$. A simple rearrangement yields

$$\mathcal{F}'_{tK} + p_t\left(\frac{J_t}{K_t}\right)^2 G' = (1+\delta)q_t - \frac{q_{t+1}}{1+i}$$

which has the usual interpretation that the annual income from a marginal unit of capital should be equal to its annual cost. The income, on the left hand side, is equal to marginal profit

[2] An alternative and more standard definition of q is to divide by the investment good price p. Our definition saves notation.

plus marginal reduction in installation costs. We add the lower cost because the installation cost function decreases in the capital stock. The full cost, on the right hand side, is the cost of purchasing and installing one unit of capital today, less the value of removing and selling the unit next year. Today's cost has to be expanded by the term $(1+\delta)$, as δ per unit is depreciated instantaneously. Next year's value must be discounted.

With a small rearrangement, we obtain the sought equations

$$\mathcal{F}'_K = p_k = \frac{q}{1+i}(i+\delta(1+i) - \frac{q_{+1}-q}{q}) - p\left(\frac{J}{K}\right)^2 G' \tag{24}$$

$$q = (1+G+\frac{J}{K}G')p \tag{25}$$

We also impose the transversality condition $\lim_{t\to\infty}\left(\frac{1}{(1+i)(1+\delta)}\right)^t q_{t+1} = 0$, which rules out speculative bubbles in the user cost equation.

Equations (19) and (20) concern the development of foreign debt, $-Z$. Given a time path for capital, the time path of foreign debt is connected to the path of per capital full consumption. The higher is full consumption, the higher is the increase in foreign debt. Equation (19) is the (Frisch) demand equation for per capita full consumption. If λ is the marginal utility of wealth of the CES utility function $\sum_t(1+n)^t(1+\rho)^{-t}H_t^{1-\sigma}$, μ equals $\lambda^{-1/\sigma}((1+i)(1-\sigma))^{1/\sigma}$. The role of equation (20) is to limit the value of μ. If μ is too high, the foreign debt will increase too fast. It is assumed that a non-zero present value of debt is not sustainable in the really long run.

It is worthwhile to discuss how equations (19) and (20) are arrived at. Equation (19) is an application of Roy's theorem where we interpret $P_t^* = \frac{(1+n)^t}{(1+i)^{t+1}}P_t$ as the price of full consumption in year t. This gives us

$$\begin{aligned} H_t &= -\frac{\frac{\partial U}{\partial P_t^*}}{\frac{\partial U}{\partial W}} \\ &= \mu\left(\frac{1+\rho}{1+i}\right)^{-t/\sigma} P_t^{-1/\sigma} \end{aligned}$$

where

$$\mu = \frac{W_{-1}}{\sum_{t=0}^{\infty}\left(\frac{1+n}{1+\rho}\right)^t\left[\frac{(1+\rho)^t}{(1+i)^{t+1}}P_t\right]^{(\sigma-1)/\sigma}}$$

Equation (20) is the "No Ponzi-Game" condition that the country cannot roll over its foreign debt indefinitely. It is a rather weak restriction on the financial behavior of a country. All the country needs to do is to pay some of the interest on its debt — in the long run. We now show that equation (20) and equation (11) (the current account) together are equal to the budget constraint of the consumer. This justifies the use of equation (20) as opposed to more severe restrictions.

Solving the current account forward by repeated substitution, and using equation (20), we obtain[3]

$$Z_{-1} = -\sum_{t=0}^{\infty}\left(\frac{1}{1+i}\right)^{t+1}(p_tX_t - p_tM_t - p_tJ_t(1+G_t) - p_tC_t + p_{tf}(\bar{F}_t - F_t) + p_{te}(\bar{E}_t - E_t)) \tag{26}$$

[3] The method of repeated substitution is reviewed, e.g., in Blanchard and Fischer (1989) pp. 218.

This equation says that the value of foreign assets equals the discounted sum of future import surpluses.

By using the definition of the profit function $\mathcal{F}_t(K_t) = p_t X_t - p_t M_t - p_{t\,f} F_t - p_{t\,e} E_t - p_{t\,l} L_t$, and recalling the definition of the value of the firm from equation (21)

$$V_{-1} = \sum_{t=0}^{\infty} \left(\frac{1}{1+i}\right)^{t+1} \mathcal{F}_t(K_t) - p_t J_t(1+G_t)$$

while the value of electricity and petroleum production is

$$\bar{V}_{-1} = \sum_{t=0}^{\infty} \left(\frac{1}{1+i}\right)^{t+1} (p_{t\,f}\bar{F}_t + p_{t\,e}\bar{E}_t)$$

we rewrite equation (26) as

$$Z_{-1} = -V_{-1} - \bar{V}_{-1} - \sum_{t=0}^{\infty} \left(\frac{1}{1+i}\right)^{t+1} (p_{t\,l} L_t - p_t C_t)$$

As the last step we use equation (8) for H_t and equation (9) for C_t, define the value of the time endowment as

$$A_{-1} = \sum_{t=0}^{\infty} \left(\frac{1}{1+i}\right)^{t+1} p_{t\,l}(1+n)^t(1+g)^t h_t T$$

define wealth as

$$W_{-1} = V_{-1} + \bar{V}_{-1} + A_{-1}$$

and use the fact that the expenditure function is homogenous of degree one in prices to obtain

$$W_{-1} \quad = \quad \sum_{t=0}^{\infty} \frac{(1+n)^t}{(1+i)^{t+1}} P_t H_t$$

This equation says that consumer wealth equals the discounted value of future full consumption.

We now turn to the steady state solution of the model. In the steady state, the interest rate must equal

$$i = (1+\rho)(1+g)^{\sigma} - 1 \tag{27}$$

in order to avoid unstainable lending or borrowing. An interpretation is that the world economy determines i to be equal to the expression on the right hand side of equation (27). Viewed from the single country perspective, it is a "razor's edge" requirement as both i and the variables on the right hand side are exogenous. As we for convenience assume a constant interest rate, equation (27) holds at all times.

Given the interest rate and the fact that the price of effective labor is constant in the steady state, we obtain the steady state growth rate of per capita full consumption as

$$\frac{H_{+1}}{H} = (1+g)$$

Since there is population growth as well, the growth in aggregate variables is

$$\frac{X_{+1}}{X} = \frac{L_{+1}}{L} = \frac{M_{+1}}{M} = \frac{E_{+1}}{E} = \frac{F_{+1}}{F} = \frac{K_{+1}}{K} = \frac{J_{+1}}{J} = \frac{C_{+1}}{C} = (1+g)(1+n)$$

The foreign debt either is zero, or changes in steady state by

$$\frac{|Z_{+1}|}{|Z|} = (1+g)(1+n)$$

It changes with $(1 + g)(1 + n)$ if that number is less than $(1 + i)$ from the transversality condition. In this case Z increases (or decreases) at a slower rate than the interest rate, and the present value of foreign debt is zero.

The foreign debt is zero in the steady state if a non-zero debt would change at a higher rate than the interest rate. This would make the present value of foreign debt infinite, which is not allowed. Thus a zero value of the foreign debt is the only possibility in that case.

Appendices

A The full set of equations

The sets referred to in the equations are defined and described in appendix C.

A.1 Indirect taxes and subsidies

$$TPV_i = \sum_{l \in pv} HTPV_{il} TART_l \quad \text{(A1)}$$

$$TVV_i = \sum_{l \in vv} HTVV_{il} TART_l \quad \text{(A2)}$$

$$TPX_i = \sum_{l \in px} HTPX_{il} TART_l \quad \text{(A3)}$$

$$TVX_i = \sum_{l \in vx} HTVX_{il} TART_l \quad \text{(A4)}$$

$$i \in va$$

$$TSV_j = \sum_{l \in sa \cup su} HTSV_{jl} TART_l \quad \text{(A5)}$$

$$j \in ps \quad \text{(A6)}$$

- TART: change in tax by proper, "budget" name
  TPV:change in ad valorem tax collected by producers
  TVV: change in ad valorem tax collected by wholesale and retail trade
  TPX: change in volume tax collected by producers
  TVX: change in volume tax collected by wholesale and retail trade
  TSV: industry (output) tax
  HTPV, HTVV, HTPX, HTPX, HTVX, HTSV: coefficients. (All but HTSV sum to unity.)

A.2 Unit costs and unit demand

$$BHS_j = (\sum_{i \in va} \lambda_{ij}^X BH_i) / \sum_{i \in va} \lambda_{ij}^X \quad \text{(A7)}$$

$$j \in ps$$

$$BH_{30} = BH_{30NUM} \quad \text{(A8)}$$

$$BH_i = BI_i \quad \text{(A9)}$$

$$i = \{00, 02, 04, 05, 36\} \subset va$$

$$BH_{89} = BH_{80} \quad \text{(A10)}$$

$$GAMP_j \sum_{i \in va} \lambda_{ij}^X BH_i = PR_j ZR_j + PM_j ZM_j + TSV_j BHS_j \quad \text{(A11)}$$

$$j \in ps \backslash \{20, 71, 89, 90\}$$

- BH: domestic price of commodities
  BHS: industry output price

BH_{30NUM}: numeraire
BI: price of imports
GAMP: base year correction term
PM: purchasers' price of material inputs
PR: purchasers' price of capital-labor-energy aggregate
TSV: industry output tax. Measured in BHS-prices for convenience. (This is an innocent choice of units).
ZM: unit demand for material inputs
ZR: unit demand for capital-labor-energy aggregate
λ^X: coefficient calculated as output of a commodity in "basic values" (evaluated by BH-prices), over total industry output in "sellers' values" (BH plus indirect taxes on the output, but not VAT)

$$PR_j = \left[aplw_j.0(PLW_j/PLW_j.0)^{rr_j.0} + aps_j.0PS_j^{rr_j.0}\right]^{1/rr_j.0} \tag{A12}$$

$$PS_j = \left[apk_j.0(PK_j/PK_j.0)^{rs_j.0} + apu_j.0PU_j^{rs_j.0}\right]^{1/rs_j.0} \tag{A13}$$

$$PU_j = \left[ape_j.0PE_j^{ru_j.0} + apf_j.0PF_j^{ru_j.0}\right]^{1/ru_j.0} \tag{A14}$$

$$j \in ps\backslash\{20, 71, 89, 90\}$$

- PE: purchasers' price of hydro power
  PF: purchasers' price of heating oil
  PLW: purchasers' price of labor
  PK: rental price of capital services
  PR: price of capital-labor-energy aggregate
  PS: price of capital-energy aggregate
  PU: price of energy
  ape.0, apf.0, apk.0, aplw.0, aps.0, apu.0: coefficients equal to base year unit demands
  PLW.0, PK.0: coefficients equal to base year purchasers' price of labor and rental price of capital services
  rr, rs, ru: coefficients equal to one less the elasticity of substitution at respective levels of aggregation. The rr_j's are based on the base year average of Hicks-Samuelson elasticities of substitution (see Frenger, 1985) computed from the estimated Generalized Leontief cost functions documented in Alfsen, Bye and Holmøy (1993). rs_j are based on the base year shadow elasticities of substitution (McFadden, 1963) documented in Alfsen, Bye and Holmøy (1993). ru_j are based on CES-function estimates by Mysen (1991).

$$ZRLW_j = aplw_j.0\left(\frac{PLW_j/PLW_j.0}{PR_j}\right)^{rr_j.0-1} \tag{A15}$$

$$ZRS_j = aps_j.0\left(\frac{PS_j}{PR_j}\right)^{rr_j.0-1} \tag{A16}$$

$$ZSK_j = apk_j.0\left(\frac{PK_j/PK_j.0}{PS_j}\right)^{rs_j.0-1} \tag{A17}$$

$$ZSU_j = apu_j.0\left(\frac{PU_j}{PS_j}\right)^{rs_j.0-1} \tag{A18}$$

$$ZUE_j = ape_j.0\left(\frac{PE_j}{PU_j}\right)^{ru_j.0-1} \tag{A19}$$

$$ZUF_j = apf_j.0\left(\frac{PF_j}{PU_j}\right)^{ru_j.0-1} \tag{A20}$$

$$j \in ps\backslash\{20, 71, 89, 90\}$$

- ZRLW: demand for labor per unit of capital-labor-energy aggregate
  ZRS: demand for capital-energy aggregate per unit of capital-labor-energy aggregate
  ZSK: demand for capital per unit of capital-energy aggregate
  ZSU: demand for energy per unit of capital-energy aggregate
  ZUE: demand for hydro power electricity per unit of energy
  ZUF: demand for heating oil per unit of energy

A.3 Prices of commodities etc.

$$\lambda^I_{jj}BI_j = PI_j + (\lambda^I_{jj} - 1)TT_jPI_j \tag{A21}$$

$$j \in va$$

- BI: import price
  PI: import price c.i.f.
  TT: change in customs duty
  λ^I: coefficient calculated as imports in basic values (BI-values) over imports in c.i.f. values (PI-values). $\lambda^I - 1$ is the rate of customs duty.

$$\begin{aligned} PM_j = {} & \sum_{i\in va}(1 + HTM_{ij}TM_i)\{(1 + HTVV_{ij}TVV_i + HTPV_{ij}TPV_i) \\ & [(\lambda^M_{ij} - \lambda^M_{ij}\lambda^{HI}_{ij}DI_i)BH_i + \lambda^M_{ij}\lambda^{HI}_{ij}DI_iBI_i] + HTVX_{ij}TVX_i\lambda^M_{ij} + HTPX_{ij}TPX_i\lambda^M_{ij}\} \\ & j \in ps \end{aligned} \tag{A22}$$

$$\begin{aligned} PE_j = {} & (1 + HTM_{71j}TM_{71})\{(\lambda^E_{71j} - \lambda^E_{71j}\lambda^{HI}_{71j}DI_{71})BH_{71} + \lambda^E_{71j}\lambda^{HI}_{71j}DI_{71}BI_{71} \\ & + HTPX_{71j}TPX_{71}\lambda^E_{71j}\} \\ & j \in ps \end{aligned} \tag{A23}$$

$$\begin{aligned} PF_j = {} & \sum_{i\in\{42,81\}\subset va}(1 + HTM_{ij}TM_i)\{(\lambda^F_{ij} - \lambda^F_{ij}\lambda^{HI}_{ij}DI_i)BH_i + \lambda^F_{ij}\lambda^{HI}_{ij}DI_iBI_i \\ & + HTVX_{ij}TVX_i\lambda^F_{ij} + HTPX_{ij}TPX_i\lambda^F_{ij}\} \\ & j \in ps \end{aligned} \tag{A24}$$

$$\begin{aligned} PC_j = {} & \sum_{i\in va}(1 + HTM_{ij}TM_i)\{(1 + HTVV_{ij}TVV_i + HTPV_{ij}TPV_i) \\ & [(\lambda^C_{ij} - \lambda^C_{ij}\lambda^{CI}_{ij}DI_i)BH_i + \lambda^C_{ij}\lambda^{CI}_{ij}DI_iBI_i] + HTVX_{ij}TVX_i\lambda^C_{ij} + HTPX_{ij}TPX_i\lambda^C_{ij}\} \\ & j \in cp \end{aligned} \tag{A25}$$

$$PC_{70} = PC_{10} \tag{A26}$$

$$
\begin{aligned}
PJ_j &= (1+HTPV_{81}TPV_{81})\sum_{i\in va}(1+HTM_{ij}TM_i)\{(1+HTPV_{ij}TPV_i) \quad (A27)\\
&\quad [(\lambda^J_{ij}-\lambda^J_{ij}\lambda^{JI}_{ij}DI_iBH_i)+\lambda^J_{ij}\lambda^{JI}_{ij}DI_iBI_i]\}\\
&\qquad j\in ja\\
PJ_{20} &= \frac{PJ_{23}J_{23}+PJ_{24}J_{24}}{J_{23}+J_{24}} \quad (A28)\\
PA_j &= \sum_{i\in va}(1+HTVV_{ij}TVV_i+HTPV_{ij}TPV_i)\lambda^A_{ij}BH_i \quad (A29)\\
&\qquad j\in va
\end{aligned}
$$

- BH, BI: domestic price and import price of commodities
  DI: import share of commodities
  J: "new" investments (explained below)
  PA: export price of commodities
  PC: consumers' price of consumption activities
  PC_{70}: price of foregners' consumption in Norway
  PE: purchasers' price of hydro power electricity
  PF: purchasers' price of heating oil
  PJ: purchasers' price of investment activity
  PJ_{20}: purchasers' price of crude oil and gas equipment
  PM: purchasers' price of material inputs
  TM: change in VAT
  TPV, TPX, TVV, TVX: change in ad valorem and volume taxes collected by producers and by wholesale and retail trade
  HTM, HTPV, HTPX, HTVV, HTVX: coefficients for VAT and other tax rates
  $\lambda^A,\lambda^C,\lambda^E,\lambda^F,\lambda^J,\lambda^M$: coefficients calculated as input of a commodity to an activity in basic value over total activity level in purchasers' value
  $\lambda^{CI},\lambda^{HI},\lambda^{JI}$: coefficients giving base year import shares (in basic values)

A.4 Wages and interest rates

$$
\begin{aligned}
GAMLW_jPLW_j &= (1+HTTF_jTF_j)WW \quad (A30)\\
WW_j &= WW/GAMLW_j \quad (A31)\\
&\qquad j\in ps
\end{aligned}
$$

- GAMLW: base year correction factor for wages
  PLW: purchasers' price of labor
  TF: change in rate of employers' contribution to social security
  WW: wage paid from employer to employee
  WW_j: base year wages from employer to employee, per industry
  HTTF: rate of employers' contribution to social security, coefficient

$$
\begin{aligned}
RENUC &= (1+rho.0)(1+g.0)^{sigma.0}-1 \quad (A32)\\
RENU &= \frac{RENUC}{1-TAXPR} \quad (A33)\\
RENUP &= \frac{1-TAXPR}{1-TAXPG}RENU \quad (A34)
\end{aligned}
$$

- RENU: (world) market interest rate
  RENUC: consumer net of tax interest rate
  RENUP: discount rate for firms
  TAXPG: personal tax rate on capital gains
  TAXPR: personal interest tax rate
  g.0: steady state rate of technical progress. Set to 0.02. This is consistent with broad evidence on long term per capita macroeconomic growth and productivity growth in Norway
  rho.0: rate of time preference. Set to 0.01.
  sigma.0: inverse of intertemporal elasticity of substitution in consumption. Set to 2 following Steigum (1993), who cites Norwegian econometric evidence in support of this value.

A.5 User costs of capital

$$GAMMA_i = \frac{ORAV_i\, UB}{RENUP + ORAV_i} \qquad i \in jr\backslash\{20\} \tag{A35}$$

$$\begin{aligned} PK_j = {} & \sum_{i \in jr} \kappa_{ij} \left\{ \frac{PJ_i}{1 + RENUP - UB} [(1 - DEBTC_j)RENUP \right. \\ & + DEPR_{ij}(1 + RENUP) + 1 \\ & -(RENUP + DEPR_{ij}(1 + RENUP) + 1)GAMMA_i] \\ & \left. + \frac{PJ_i}{1 + RENUP} DEBTC_j RENU - \frac{(1 - GAMMA_i)PJ_i(+1)}{1 + RENUP - UB} \right\} \\ & \qquad j \in \{40, 55, 80, 81\} \subset ps \end{aligned} \tag{A36}$$

$$QJ_i = PJ_i[beta.0(\frac{JKS_{30}}{K_{30}} - gamma.0) + 1] \qquad i \in ja \tag{A37}$$

$$\begin{aligned} PK_{30} = {} & \sum_{i \in jr} \kappa_{ij} \left\{ \frac{QJ_i}{1 + RENUP - UB} (RENUP + DEPR_{ij}(1 + RENUP) + 1) \right. \\ & - \frac{QJ_i(+1)}{1 + RENUP - UB} + DEBTC_{30} PJ_i (\frac{RENU}{1 + RENUP} - \frac{RENUP}{1 + RENUP - UB}) \\ & - \frac{(PJ_i(RENUP + DEPR_{ij}(1 + RENUP) + 1) - PJ_i(+1))GAMMA_i}{1 + RENUP - UB} \\ & \left. - \frac{(1 + RENUP)PJ_i}{1 + RENUP - UB} \frac{beta.0}{2} (\left(\frac{JKS_{30}}{K_{30}} \right)^2 - gamma.0^2) \right\} \end{aligned} \tag{A38}$$

$$\begin{aligned} PK_{83} = {} & PJ_{10} [RENUC + DEPR_{1083}(1 + RENUC) + 1 - TAXWN \\ & + 0.2(0.025\, TAXPR + TAXWN + TAXE)] - PJ_{10}(+1) \end{aligned} \tag{A39}$$

- DEBTC: debt-equity share
  DEPR: rate of depreciation
  GAMMA: help variable
  JKS_{30}: investment in industry 30
  K_{30}: capital in industry 30
  ORAV: rate of (ordinary) depreciation allowance
  PJ: purchasers' price of investment goods

PK: rental price of capital services
QJ: shadow price of installed investments
RENU, RENUC, RENUP: interest rate, consumer net of tax interest rate and discount rate for firms
TAXE: personal property tax
TAXPR: personal tax on interest income
TAXWN: personal wealth tax
UB: corporate income tax
beta.0, gamma.0: coefficients in installation cost function. *gamma.0* is calibrated to the base year ratio of JKS_{30}/K_{30}. *beta.0* equals 10.
κ: coefficients indicating the share of an asset in total industry capital.

A.6 Depreciation rates

$$
\begin{aligned}
DEPR_{10j} &= -DEPX + \text{if } \frac{SUM_{01}}{SUM_{01}.0} < 1000korrb.0/(2korrc.0) \text{ then} \\
&\qquad \delta_{10j} + \frac{korrb.0}{1000}\frac{SUM_{01}}{SUM_{01}.0} - \frac{korrc.0}{(1000)^2}\left(\frac{SUM_{01}}{SUM_{01}.0}\right)^2 \\
&\quad \text{else} \quad \delta_{10j} + \frac{korrb.0^2}{4korrc.0} \\
&\qquad\qquad j \in ps\backslash\{90\}
\end{aligned}
\tag{A40}
$$

$$
\begin{aligned}
DEPR_{1090} &= -DEP90X + \text{if } \frac{BENSIN{+}DIESEL}{BENSIN.0 + DIESEL.0} < 1000piggb.0/(2piggc.0) \text{ then} \\
&\qquad \delta_{1090} + \frac{piggb.0}{1000}\frac{BENSIN + DIESEL}{BENSIN.0{+}DIESEL.0} - \frac{piggc.0}{(1000)^2}\left(\frac{BENSIN{+}DIESEL}{BENSIN.0{+}DIESEL.0}\right)^2 \\
&\quad \text{else} \quad \delta_{1090} + \frac{piggb.0^2}{4piggc.0}
\end{aligned}
\tag{A41}
$$

- BENSIN: total gasoline consumption (in 1000 metric tons)
  DEPR: rate of depreciation
  DEPX, DEP90X: base year correction of depreciation
  DIESEL: total autodiesel consumption (in 1000 metric tons)
  SUM_{01}: emissions of SO_2 (in metric tons)
  korrb.0, korrc.0: coefficients in equation for corrosion. *korrb.0* is based on the evidence in Brendemoen et.al. (1992). *korrc.0* is calibrated to make the maximum depreciation three times the base year acual (which is 2.5 per cent).
  piggb.0, piggc.0: coefficients in equation for road depreciation. *piggb.0* is based on the evidence in Brendemoen et.al. (1992). *piggc.0* is calculated to make the maximum road depreciation three times the base year actual (which is 0.75 per cent).
  BENSIN.0, DIESEL.0: coefficients for base-year consumption of gasoline and autodiesel
  $SUM_{01}.0$: coefficient for base-year emission of SO_2.
  δ: depreciation at base year corrosion. From the National accounts.

A.7 Commodity market equilibrium

$$\sum_{j\in va} \lambda_{ij}^{I} I_j + \sum_{j\in pa} \lambda_{ij}^{X} X_j = \sum_{j\in ps} \left(\lambda_{ij}^{M} M_j + \lambda_{ij}^{E} E_j + \lambda_{ij}^{F} F_j\right) + \sum_{j\in cp} \lambda_{ij}^{C}(C_j - CK_j)$$

$$+\sum_{j\in ja}\lambda^J_{ij}J_j+\sum_{j\in va}\lambda^A_{ij}A_j+DSI_i+DSH_i \tag{A42}$$
$$i\in va$$
$$X80=X8080+X8089 \tag{A43}$$
$$X89=0 \tag{A44}$$

- A: exports
  C: consumption
  CK: purchases of used real capital from corporate sector (cars)
  DSH: changes in stocks of domestic production
  DSI: changes in stocks of imports
  E: electricity input
  F: heating oil input
  I: imports
  M: material inputs
  X: gross production
  $\lambda^A,\lambda^C,\lambda^E,\lambda^F,\lambda^J,\lambda^F,\lambda^X$: activity share coefficients

A.8 Imports by activity

$$\lambda^I_{ii}I_i-DSI_i = [\,m^A_iA_i+\sum_{j\in ps}\left(\lambda^M_{ij}\lambda^{HI}_{ij}M_j+\lambda^E_{ij}\lambda^{HI}_{ij}E_j+\lambda^F_{ij}\lambda^{HI}_{ij}F_j\right) \tag{A45}$$
$$+\sum_{j\in cp}\lambda^C_{ij}\lambda^{CI}_{ij}(C_j-CK_j)+\sum_{j\in ja}\lambda^J_{ij}\lambda^{JI}_{ij}J_j\,]\,DI_i \tag{A46}$$
$$i\in va$$

- A, C, CK, DI, DSI, E, F, I, J, M: exports, consumption, purchases of used real capital, import share, changes in import stocks, electricity, heating oil, imports, investments, material input
  $\lambda^C,\lambda^E,\lambda^F,\lambda^J,\lambda^M$: activity share coefficients
  $\lambda^{CI}_{ij},\lambda^{HI}_{ij},\lambda^{JI}_{ij}$: import share coefficients
  m^A: coefficient, re-export as a share of exports

$$IA_i = m^A_iDI_iA_i \tag{A47}$$
$$i\in va$$

- A: exports
  DI: import share
  IA: re-exported imports
  m^A: coefficient, re-exports as a share of exports

A.9 Factor demand

$$M_j = ZM_jX_j \tag{A48}$$
$$E_j = ZUE_jZSU_jZRS_jZR_jX_j \tag{A49}$$
$$F_j = ZUF_jZSU_jZRS_jZR_jX_j \tag{A50}$$

$$
\begin{aligned}
PLW_j.0 * LW_j &= ZRLW_j ZR_j X_j & \text{(A51)}\\
PK_j.0 * K_j &= ZSK_j ZRS_j ZR_j X_j & \text{(A52)}\\
& \qquad j \in ps \backslash \{20, 71, 89, 90\}
\end{aligned}
$$

- E: input of hydro power
  F: input of heating oil
  K: capital input
  LW: labor input in efficiency units
  M: material input
  X: gross production
  ZM: material input as a share of gross production
  ZRLW: labor as a share of capital-labor-energy aggregate
  ZRS:capital-energy as a share of capital-labor-energy aggregate
  ZSK: capital as a share of capital-energy aggregate
  ZSU: energy as a share of capital-energy aggregate
  ZUE: hydro power as a share of energy
  ZUF: heating oil as a share of energy
  PLW.0, PK.0: coefficients for base year price of labor and capital

$$
\begin{aligned}
M_j &= ZM_j X_j & \text{(A53)}\\
E_j &= ZE_j X_j & \text{(A54)}\\
F_j &= ZF_j X_j & \text{(A55)}\\
LW_j &= ZLW_j X_j & \text{(A56)}\\
& \qquad j \in \{20, 71\}
\end{aligned}
$$

- ZE: hydro power as a share of gross production
  ZF: heating oil as a share of gross production
  ZLW: labor input as a share of gross production
  ZM: material input as a share of gross production

$$
\begin{aligned}
K_{20} &= \sum_{i \in jr} K_{i20} & \text{(A57)}\\
K_{i20} &= \frac{K_{i20}(-1) + JK_{i20}}{1 + DEPR_{i20}} & \text{(A58)}\\
& \qquad i \in jr \backslash \{30\}\\
K_{71} &= ZK_{71} X_{71} & \text{(A59)}
\end{aligned}
$$

- DEPR: depreciation ratio
  JK: gross real investment
  K: capital. K_{20} is the sum of asset specific capital
  X: gross production
  ZK: capital as a share of gross production

$$
\begin{aligned}
E_{89} &= 0 & \text{(A60)}\\
F_{89} &= 0 & \text{(A61)}\\
LW_{89} &= 0 & \text{(A62)}\\
K_{89} &= 0 & \text{(A63)}
\end{aligned}
$$

M_{89} (exogenous) is not zero.

$$
\begin{aligned}
M_{90} &= ZHM_{90}H_{90} && \text{(A64)}\\
E_{90} &= ZHE_{90}H_{90} && \text{(A65)}\\
F_{90} &= ZHF_{90}H_{90} && \text{(A66)}
\end{aligned}
$$

- H_{90}: activity index, public sector
  ZHE: hydro power as a share of activity
  ZHF: heating oil as a share of activity
  ZHM: material inputs as a share of activity

A.10 Investment

$$
\begin{aligned}
JK_{i20} &= J_{i20} - JE_i && \text{(A67)}\\
&\qquad i \in ja\backslash\{30\} &&\\
JK_{2020} &= JK_{2320} + JK_{2420} && \text{(A68)}\\
J_j &= J_{j20} && \text{(A69)}\\
&\qquad j \in \{23, 24\} \subset ja &&\\
JK_j &= J_j - JE_j && \text{(A70)}\\
&\qquad j \in \{23, 24\} \subset ja &&\\
JE_{20} &= JE_{23} + JE_{24} && \text{(A71)}
\end{aligned}
$$

- J: new investments (including installation costs)
  JE: sales of used real capital
  JK: gross real investments by activity

$$
\begin{aligned}
J_i &= JK_{i20} + \sum_{j \in ps} \left[(DEPR_{ij} + 1) K_j - K_j(-1) \right] \kappa_{ij} + JE_i + JR_i && \text{(A72)}\\
&\quad + \left[(1 + DEPR_{i30}) K_{30} - K_{30}(-1) \right] \kappa_{i30} \frac{beta.0}{2} \frac{\left(\frac{JKS_{30}}{K_{30}} - gamma.0\right)^2}{\frac{JKS_{30}}{K_{30}}} &&\\
&\quad i \in jr &&
\end{aligned}
$$

- DEPR: rate of depreciation
  J: new investments
  JE: sales of used real capital
  JK: gross real investments by activity
  JKS_{30}: gross real investments in industry 30
  JR: base year correction term
  K: capital input
  beta.0, gamma.0: coefficients in the installation cost function. *gamma.0* equals base-year JKS_{30}/K_{30}. *beta.0* is 10.
  κ: coefficient for an asset's share of capital

A.11 Consumer behavior

$$
\begin{aligned}
C_i - \zeta_i C_{70} &= \frac{BC_i.0}{PC_i} VC && \text{(A73)} \\
PC &= \prod_{i \in cp} PC_i^{BC_i.0} && \text{(A74)} \\
VC &= PC * C && \text{(A75)}
\end{aligned}
$$

$$i \in cp$$

- C_i: consumption activity i
  C_{70}: foreigners' consumption in Norway
  C: consumption aggregate
  PC_i: purchasers' price of consumption activity i
  PC: price of consumption aggregate
  VC: consumption expenditure
  BC.0: coefficient for budget share
  ζ: coefficient distributing foreigners' consumption in Norway on consumption activities. ζ_{30} is minus one as C_{70} formally is negative. The remaining ζ's are zero.

$$
\begin{aligned}
WWC &= (1 - TAXP)WW && \text{(A76)} \\
P &= \left[aclw.0(HEALTH * WWC/WWC.0)^{rp.0} + acc.0PC^{rp.0}\right]^{1/rp.0} && \text{(A77)} \\
POP &= POPEX - POPNED/POP89.0 && \text{(A78)}
\end{aligned}
$$

- HEALTH: index of health induced productivity
  P: price index of full consumption
  PC: price index of consumption aggregate
  POP: Index of population
  POPEX: Index of exogenous population projection
  POPNED: Deaths because of traffic accidents
  TAXP: tax rate on wages
  WW: gross wage rate
  WWC: net wage rate
  acc.0, aclw.0: coefficients calibrated to base year consumption share of full consumption and the value of leisure as share of full consumption
  POP89.0: coefficient, base year population
  rp.0: coefficient, one less the elasticity of substitution between leisure and goods. *rp*.0 is -3, which is consistent with an uncompensated labor supply elasticity of 0.3 and a compensated elasticity of 0.4. Norwegian econometric evidence on labor supply (Dagsvik and Strøm (1992)) indicate the labor supply elasticities to be at least this large, and the income effect on labor supply to be insignificant.
  WWC.0: coefficient, base year wage rate

$$
\begin{aligned}
WWC.0 * LW &= POP * HEALTH[WWC.0 * HOURS * EPS && \text{(A79)} \\
&\quad - aclw.0\left(\frac{HEALTH * WWC/WWC.0}{P}\right)^{rp.0-1} H] \\
C &= POP * acc.0\left(\frac{PC}{P}\right)^{rp.0-1} H && \text{(A80)}
\end{aligned}
$$

- C: consumption quantity index
  EPS: (labor augmenting) productivity index. Grows $(1+g)$ per year
  H: index of full consumption
  HEALTH: index of health induced productivity
  LW: labor supply in efficiency units
  P: price of full consumption
  PC: price of consumption quantity index
  POP: index of population
  HOURS: time endowment
  WWC: net wage rate
  acc.0, aclw.0, rp.0, WWC.0: coefficients, see the comments to equation (A76).

$$H = MU * P^{(-1/sigma.0)} EPS \tag{A81}$$

- EPS: productivity index
  H: index of full consumption
  MU: constant of consumption related to the "marginal utility of wealth"
  P: price of full consumption
  sigma.0: inverse of intertemporal elasticity of substitution. Equals 2, see the comments to equation (A34).

$$\begin{aligned}
D_1 &= b_1.0(SUM_{01} + SUM_{02}) && \text{(A82)}\\
D_2 &= b_2.0(SUM_{01} + SUM_{02}) && \text{(A83)}\\
D_3 &= b_{3\,01}.0(am_{01}.0M_{01\,SUM} + as_{01}.0S_{01\,SUM})/2 && \text{(A84)}\\
D_4 &= b_{3\,02}.0(am_{02}.0M_{02\,SUM} + as_{02}.0S_{02\,SUM})/2 && \text{(A85)}\\
D_5 &= b_{3\,03}.0(am_{03}.0M_{03\,SUM} + as_{03}.0S_{03\,SUM})/2 && \text{(A86)}\\
D_6 &= b_{3\,06}.0(am_{06}.0M_{06\,SUM} + as_{06}.0S_{06\,SUM})/2 && \text{(A87)}\\
& \{01, 02, 03, 06\} \subset komp &&\\
D_8 &= b_5.0(BENSIN + DIESEL) * 0.8 && \text{(A88)}\\
D_9 &= b_6.0(BENSIN + DIESEL) && \text{(A89)}\\
D_{11} &= b_8.0(BENSIN + DIESEL)/2 && \text{(A90)}\\
D_7 &= D_{10} = 0 && \text{(A91)}\\
D &= \sum_{i=1}^{11} D_i && \text{(A92)}
\end{aligned}$$

- BENSIN: total gasoline consumption
  D_1: disutility from acidification of lakes
  D_2: disutility from acidification of forests
  D_3: health damage from emissions of SO_2
  D_4: health damage from emissions of NO_x
  D_5: health damage from emissions of CO
  D_6: health damage from emissions of particulates
  D_8: disutility from traffic accidents
  D_9: disutility from congestion
  D_{11}: disutility from traffic noise

D: sum of disutilities from external effects
DIESEL: total autodiesel consumption (in 1000 metric tons)
M_{jSUM}: total emissions from mobile sources (in metric tons)
S_{jSUM}: total emissions from stationary sources (in metric tons)
SUM_{01}, SUM_{02}: sum of emissions (mobile, stationary, process) of SO_2 and NO_x
am.0, as.0: coefficients for fraction of emissions that cause health damage
b.0: coefficients for disutility (in NOK) as a share of source of disutility (emissions, gasoline & diesel consumption etc.)

$$HEALTH = 1 - HEALX \tag{A93}$$
$$- \sum_{\substack{j\in\{01,02,\\03,06\}\subset komp}} \{\text{if } \frac{am_j.0M_{j\,SUM} + as_j.0S_{j\,SUM}}{am_j.0M_{j\,SUM}.0 + as_j.0S_{j\,SUM}.0} < 1000heab_j.0/(2heac_j.0) \text{ then}$$
$$\left[\frac{heab_j.0}{1000}\frac{am_j.0M_{j\,SUM} + as_j.0S_{j\,SUM}}{am_j.0M_{j\,SUM}.0 + as_j.0S_{j\,SUM}.0} - \frac{heac_j.0}{(1000)^2}\left(\frac{am_j.0M_{j\,SUM} + as_j.0S_{j\,SUM}}{am_j.0M_{j\,SUM}.0 + as_j.0S_{j\,SUM}.0}\right)^2\right]$$
$$\text{else } \frac{heab_j.0^2}{4heac_j.0}\} - \{\text{if } \frac{BENSIN + DIESEL}{BENSIN.0 + DIESEL.0} < 1000stoyb.0/(2stoyc.0) \text{ then}$$
$$\left[\frac{stoyb.0}{1000}\frac{BENSIN + DIESEL}{BENSIN.0 + DIESEL.0} - \frac{stoyc.0}{(1000)^2}\left(\frac{BENSIN + DIESEL}{BENSIN.0 + DIESEL.0}\right)^2\right]$$
$$\text{else } \frac{stoyb.0^2}{4stoyc.0}\} - PPULYK$$

- HEALTH: index of health induced productivity
  HEALX: base year correction factor
  $M_{j\,SUM}$: total mobile emissions (in metric tons)
  PPULYK: index of productivity loss from traffic accidents
  $S_{j\,SUM}$: total stationary emissions (in metric tons)
  heab.0, heac.0: coefficients for the productivity loss from emissions to air. *healb.0* equals b_3, see the discussion in section 2. *healc.0* is calibrated to the maximum health productivity loss, which is 3 per cent in the cases of NO_x and particulates, and 1.5 per cent in the cases of SO_2 and CO.
  am.0, as.0: coefficients for fraction of emissions that cause health damage
  $M_{j\,SUM}.0$, $S_{j\,SUM}.0$: coefficients, base year emissions from mobile and stationary sources

  stoyb.0, stoyc.0: coefficients for productivity loss from noise. *stoyb.0* equals one half of b_8, see the discussion in section 2. *stoyc.0* is calibrated to the maximum productivity loss from noise, which is 1 per cent.
  BENSIN.0, DIESEL.0: coefficients for base-year consumption of gasoline and autodiesel.

A.12 Traffic accidents

$$FFLVBENS = 1282 * BENSIN \tag{A94}$$
$$FFLVDIES = 1204.8 * DIESEL \tag{A95}$$

- BENSIN, DIESEL: gasoline, auto-diesel consumption (in 1000 metric tonnes)
  FFLVBENS: gasoline consumption (in litres). There are 1284 litres per metric ton of gasoline
  FFLVDIES: auto-diesel consumption (in litres). There are 1204.8 litres per metric ton of auto-diesel

$$KMBENS = akmben.0 * FFLVBENS * e^{ADEBENS*YEAR} \tag{A96}$$

$$KMDIES = akmdie.0 * FFLVDIES * e^{ADEDIES*YEAR} \tag{A97}$$

$$ROADS = aroads.0 + atroad.0 \ln(YEAR + 1989 - 1965) \tag{A98}$$

$$CROWD = \frac{\frac{ROADS}{KMBENS+KMDIES}}{\frac{ROAD89.0}{KMBE89.0+KMDI89.0}} \tag{A99}$$

- ADEBENS: index of autonomous change in gasoline efficiency
  ADEDIES: index of autonomous change in auto-diesel efficiency
  CROWD: index of crowding on roads
  FFLVBENS, FFLVDIES: gasoline, auto-diesel consumption (in litres)
  KMBENS: total kilometres road work by gasoline powered vehicles
  KMDIES: total kilometres road work by auto-diesel powered vehicles
  ROADS: estimated road capital stock (equal to *aroads.0* plus *atroad.0* in 1965)
  YEAR: number of years (0 in base year 1989)
  akmben.0, akmdie.0: coefficients for base year automobile efficiency, kilometres road work per litre gasoline and auto- diesel
  aroads.0, atroad.0: coefficients in equation for road capital stock.
  KMBE89.0, KMDI89.0: coefficients for base year total kilometres road work
  ROAD89.0: coefficient for base year road capital stock

$$\begin{aligned}\frac{TRSKADDE - TRSKADDE(-1)}{TRSKADDE(-1)} &= atstre.0 \\ &+ atsben.0 \left(\frac{KMBENS(-1)}{KMBENS(-1) + KMDIES(-1)}\right)\left(\frac{KMBENS - KMBENS(-1)}{KMBENS(-1)}\right) \\ &+ (atsben.0 \left(\frac{KMDIES(-1)}{KMBENS(-1) + KMDIES(-1)}\right) + atsbus.0)\left(\frac{KMDIES - KMDIES(-1)}{KMDIES(-1)}\right) \\ &+ atscro.0 \left(\frac{CROWD - CROWD(-1)}{CROWD(-1)}\right)\end{aligned} \tag{A100}$$

$$\begin{aligned}LLLANED &= (atsbte.0 + atsbtb.0)(TRSKADDE - tska_{89}.0) \\ &+ \sum_{i=0}^{8} atsjo_i.0(TRSKADDE(-i) - tska_{89-i}.0) \\ &+ alainv.0 \sum_{i=1}^{37}(TRSKADDE(-i) - tska_{89-i}.0)\end{aligned} \tag{A101}$$

$$POPNED = aladoe.0 \sum_{i=0}^{37}(TRSKADDE(-i) - tska_{89-i}.0) \tag{A102}$$

$$PPULYK = LLLANED/(POP * LW89.0) \tag{A103}$$

- CROWD, KMBENS, KMDIES: Crowding on roads, kilometres road work from gasoline powered cars
  LLLANED: reduced labor supply (among living) because of traffic accidents
  POP: population index
  POPNED: reduced population because of traffic accidents (in hours)
  PPULYK: reduced labor productivity because of traffic accidents
  TRSKADDE: number of people injured in traffic accidents
  atsben.0, atsbus.0, atscro.0, atstre.0: coefficients, elasticities of traffic casualties w.r.t. gasoline, auto-diesel and crowding. *atstre.0* is a constant.
  aladoe.0, alainv.0:coefficients for number of people dead (*aladoe.0*) or permanently injured (*alainv.0*)
  atsbtb.0, atsbte, atsjo$_i$.0: coefficients for number of people having injured children 'this year' (*atsbtb.0*), being injured themselves 'this year' (*atsbte.0*), being injured for i years (*atsjo$_i$.0*).
  LW89.0: coefficient, base year labour supply
  tska$_{89-i}$.0: coefficients for number of traffic casualties in the base path (these are all equal).

A.13 Factor market equilbrium

$$LW = \sum_{j \in ps} LW_j \tag{A104}$$

- LW: labor supply in efficiency units
  LW_j: labor demand by industry j, in efficiency units

$$K = \sum_{j=ps} K_j \tag{A105}$$

- K: capital stock
  K_j: capital stock in industry j

A.14 Inventories

$$\begin{array}{rcl} DSI_i + DSH_i & = & 0.1 \left[\lambda_{ii}(I_i - I_i(-1)) + \sum_{i \in pa} \lambda_{ij}^X (X_j - X_j(-1)) \right] + DSE_i \\ & & i \in va \end{array} \tag{A106}$$

- DSE: base year correction of inventories
  DSH: change in inventories of domestic production
  DSI: change in inventories of imported goods
  I: imports
  X: gross production
  λ^X, λ^I: activity share coefficients

A.15 Export market shares and sector prices

$$MA_i = \frac{\sum_{j \in va} \lambda^A_{ij} A_j - IA_i}{\sum_{j \in pa} \lambda^X_{ij} X_j} \qquad i \in va \tag{A107}$$

- A: exports
  IA: reexported imports
  MA: export market share, exports as a share of production
  X: gross production
  λ^A, λ^X: activity share coefficients

$$BS_i = MA_i PA_i + (1 - MA_i) BH_i \qquad i \in va \tag{A108}$$

- BH: basic price of domestically produced goods
  BS: average basic price for domestically produced goods
  MA: export market share
  PA: export price

A.16 Taxes, VAT and customs duty

$$\begin{aligned} TVPV_i = & \Bigg[\sum_{j \in ps} HTPV_{ij} \lambda^M_{ij} [(1 - \lambda^{HI}_{ij} DI_i) BH_i + \lambda^{HI}_{ij} DI_i BI_i] M_j \\ & + \sum_{j \in cp} HTPV_{ij} \lambda^C_{ij} [(1 - \lambda^{CI}_{ij} DI_i) BH_i + \lambda^{CI}_{ij} DI_i BI_i] (C_j - CK_j) \\ & + \sum_{j \in ja} HTPV_{ij} \lambda^J_{ij} [(1 - \lambda^{JI}_{ij} DI_i) BH_i + \lambda^{JI}_{ij} DI_i BI_i] J_j \Bigg] TPV_i \end{aligned} \tag{A109}$$

$$\begin{aligned} TVVV_i = & \Bigg[\sum_{j \in ps} HTVV_{ij} \lambda^M_{ij} [(1 - \lambda^{HI}_{ij} DI_i) BH_i + \lambda^{HI}_{ij} DI_i BI_i] M_j \\ & + \sum_{j \in cp} HTVV_{ij} \lambda^C_{ij} [(1 - \lambda^{CI}_{ij} DI_i) BH_i + \lambda^{CI}_{ij} DI_i BI_i] (C_j - CK_j) \\ & + \sum_{j \in va} HTVV_{ij} \lambda^A_{ij} PA_j A_j \Bigg] TVV_i \end{aligned} \tag{A110}$$

$$\begin{aligned} TVPX_i = & \Bigg[\sum_{j \in ps} HTPX_{ij} \lambda^M_{ij} M_j + \sum_{j \in va} HTPX_{ij} \lambda^E_{ij} E_j \\ & + \sum_{j \in cp} HTPX_{ij} \lambda^C_{ij} (C_j - CK_j) \Bigg] TPX_i \end{aligned} \tag{A111}$$

$$TVVX_i = \left[\sum_{j\in ps} HTVX_{ij}\lambda^M_{ij}M_j + \sum_{j\in va} HTVX_{ij}\lambda^F_{ij}F_j \right. \qquad (A112)$$
$$\left. + \sum_{j\in cp} HTVX_{ij}\lambda^C_{ij}(C_j - CK_j)\right] TVX_i$$
$$i \in va$$

- BH, BI, PA: basic price, import price, price of exports
  CK: purchases of used real capital by households from corporate sector
  DI: import share
  A, C, E, F, J, M: exports, consumption, electricity, heating oil, investments, material inputs
  TPV: change in value added tax collected from producers
  TPX: change in volume tax collected from producers
  TVV: change in value added tax collected from wholesale and retail trade
  TVX: change in volume tax collected from wholesale and retail trade
  TVPV: net ad valorem taxes on a commodity collected from producers
  TVPX: net volume taxes on a commodity collected from producers
  TVVV: net ad valorem taxes on a commodity collected from wholesale and retail trade
  TVVX: net volume taxes on a commodity collected from wholesale and retail trade
  HTPX, HTPV, HTVX, HTVV: coefficients for ad valorem and volume taxes collected from producers, and wholesale and retail trade
  $\lambda^A, \lambda^C, \lambda^E, \lambda^F, \lambda^J, \lambda^M$: activity share coefficients
  $\lambda^{CI}, \lambda^{HI}, \lambda^{JI}$: import share coefficients

$$XMT_i = \sum_{j\in ps} HTM^H_{ij}(1 + HTVV_{ij} + HTPV_{ij} + HTVX_{ij} + HTPX_{ij})(\lambda^M_{ij}M_j + \lambda^E_{ij}E_j + \lambda^F_{ij}F_j)$$
$$+ \sum_{j\in cp} HTM^C_{ij}(1 + HTVV_{ij} + HTPV_{ij} + HTVX_{ij} + HTPX_{ij})\lambda^C_{ij}(C_j - CK_j)$$
$$+ \sum_{j\in ja} HTM^J_{ij}(1 + HTVV_{ij} + HTPV_{ij} + HTVX_{ij} + HTPX_{ij})\lambda^J_{ij}J_j \qquad (A113)$$

$$TMT_i = \left[\sum_{j\in ps} HTM^H_{ij}[(1 + HTVV_{ij}TVV_i + HTPV_{ij}TPV_i)((1 - \lambda^{HI}_{ij}DI_i)BH_i + \lambda^{HI}_{ij}DI_iBI_i)\right.$$
$$+HTVX_{ij}TVX_i + HTPX_{ij}TPX_i](\lambda^M_{ij}M_j + \lambda^E_{ij}E_j + \lambda^F_{ij}F_j)$$
$$+ \sum_{j\in cp} HTM^C_{ij}[(1 + HTVV_{ij}TVV_i + HTPV_{ij}TPV_i)((1 - \lambda^{CI}_{ij}DI_i)BH_i + \lambda^{CI}_{ij}DI_iBI_i)$$
$$+HTVX_{ij}TVX_i + HTPX_{ij}TPX_i]\lambda^C_{ij}(C_j - CK_j)$$
$$+ \sum_{j\in ja} HTM^J_{ij}[(1 + HTVV_{ij}TVV_i + HTPV_{ij}TPV_i)((1 - \lambda^{JI}_{ij}DI_i)BH_i + \lambda^{JI}_{ij}DI_iBI_i)$$
$$\left.+HTVX_{ij}TVX_i + HTPX_{ij}TPX_i]\lambda^J_{ij}J_j\right] TM_i \qquad (A114)$$
$$i \in va$$

New symbols compared with equations (A109) to (A112) are

- TM: change in VAT
  TMT: VAT accrued on a commodity
  XMT: fixed-price index of VAT accrued on a commodity
  HTM^C, HTM^H, HTM^J: coefficients for activity specific VAT rate on a commodity

$$XIT_i = HSJA_iJ_i\Bigg[\sum_{j\in va}(1+HTM^J_{ij})[1+HTVV_{ij}+HTPV_{ij} + HTVX_{ij}+HTPX_{ij}]\lambda^J_{ij}\Bigg] \tag{A115}$$

$$TIT_i = HSJA_iJ_i\Bigg[\sum_{j\in va}(1+HTM^J_{ij}TM_j)[(1+HTVV_{ij}TVV_j+HTPV_{ij}TPV_j) ((1-\lambda^{JI}_{ij}DI_j)BH_j+\lambda^{JI}_{ij}DI_jBI_j)+HTVX_{ij}TVX_j+HTPX_{ij}TPX_j]\lambda^J_{ij}\Bigg]TPV_{81} \quad i\in ja \tag{A116}$$

New symbols compared with equations (A109) to (A114) are

- TIT: accrued investment levy on a commodity
  XIT: fixed-price accrued investment levy on a commodity
  $HSJA$: coefficients for rate of investment levy on commodity

$$TVPI_i = TVPX_i + TVPV_i \quad i\in\{00,02\}\subset va \tag{A117}$$

$$TVPI_i = HPVB_iBI_i\lambda^I_{ii}I_iTPV_i + HPXB_i\lambda^I_{ii}I_iTPX_i \quad i\in va\backslash\{00,02\} \tag{A118}$$

- BI: price of imports
  I: imports
  TPV, TPX: change in ad valorem and volume taxes collected from producers
  TVPI: ad valorem and volume taxes on imports
  $HPVB$, $HPXB$: coefficients for tax rates on imports

$$YTV_j = \sum_{i\in va}HTF_{ij}(TVPV_i+TVPX_i-TVPI_i) \quad j\in ps\backslash\{81\} \tag{A119}$$

$$YTV_{81} = \sum_{i\in va}TVVV_i+TVVX_i \tag{A120}$$

$$YTS_j = BHS_jTSV_jX_j \quad j\in ps \tag{A121}$$

- BHS: basic price of industry output
  TSV, TVPI, TVPV, TVPX, TVVV, TVVX: industry output tax, tax on imports accrued on a commodity, ad valorem and volume taxes collected from producers and wholesale and retail trade, all accrued on commodities
  X: gross production
  YTV: net commodity taxes assigned to an industry
  YTS: net output taxes by industry
  HTF: coefficient for commodity taxes by industry of origin

A.17 Production and income in tax collecting industries

$$Q_{51} = \sum_{i \in va} HTB_i \lambda^I_{ii} I_i \quad \text{(A122)}$$

$$Y_{51} = \sum_{i \in va} HTB_i \lambda^I_{ii} I_i TT_i PI_i \quad \text{(A123)}$$

$$Q_{54} = \sum_{j \in ja} XIT_j \quad \text{(A124)}$$

$$Y_{54} = \sum_{j \in ja} TIT_j \quad \text{(A125)}$$

$$Q_{57} = \sum_{i \in va} (HPVB_i + HPXB_i) \lambda^I_{ii} I_i \quad \text{(A126)}$$

$$Y_{57} = \sum_{i \in va} TVPI_i \quad \text{(A127)}$$

$$Q_{59} = \sum_{i \in va} XMT_i \quad \text{(A128)}$$

$$Y_{59} = \sum_{i \in va} TMT_i \quad \text{(A129)}$$

- I, PI: imports and price of imports
  Q: gross product in fixed ("real") prices
  TIT: accrued investment levy
  TMT: accrued VAT
  TT: change in rate of customs duty
  TVPI: accrued ad valorem and volume taxes on imports
  XIT: fix-price accrued investment levy
  XMT: fix-price accrued VAT
  Y: gross product in current value
  HTB: coefficients for customs duty (equal to $(\lambda^I - 1)/\lambda^I$)
  HPVB, HPXB: coefficients, rates of excise taxes on imports
  λ^I: coefficient calculated as imports in basic values (BI-values) over imports in c.i.f. values (PI-values).

$$YTS_j = 0 \quad \text{(A130)}$$

$$YTV_j = Y_j \quad \text{(A131)}$$

$$YE_j = 0 \quad \text{(A132)}$$

$$X_j = Q_j \quad \text{(A133)}$$

$$FD_j = 0 \quad \text{(A134)}$$

$$YD_j = 0 \quad \text{(A135)}$$

$$j \in \{51, 54, 57, 59\} \subset psk$$

- FD: depreciation, fixed prices
  Q: gross product, fixed prices
  X: gross production
  YD: depreciation, current prices

YE: operating surplus
YT: total net indirect taxes accrued on industry
YTS, YTV: industry output taxes and commodity taxes assigned to industry

A.18 Wages and employers' contributions to National Insurance

$$YWW_j = LW_j WW_j \tag{A136}$$
$$YWT_j = HTF_j TF_j YWW_j \tag{A137}$$
$$j \in ps$$

- LW: labor input in efficiency units
  TF: change in employers' contribution to national insurance
  WW: gross wage rate, efficiency units
  YWT: employers' contribution to national insurance
  YWW: wage income
  HTF: coefficient for rate of employers' contribution to national insurance

A.19 Capital depreciation and investment

$$FD_j = \left(\sum_{i \in jr} \kappa_{ij} DEPR_{ij}\right) K_j \tag{A138}$$
$$j \in ps\backslash\{20\}$$
$$FD_{20} = \left(\sum_{i \in jr} DEPR_{i20} K_{i20}\right) \tag{A139}$$
$$YD_j = \left(\sum_{i \in jr} \kappa_{ij} DEPR_{ij} PJ_i\right) K_j \tag{A140}$$
$$j \in ps\backslash\{20\}$$
$$YD_{20} = \left(\sum_{i \in jr} DEPR_{i20} PJ_i K_{i20}\right) \tag{A141}$$

- DEPR: rate of depreciation
  FD: depreciation, fixed prices
  K: capital
  PJ: purchasers' price of investment goods
  YD: depreciation, current prices

$$JKS_j = \sum_{i \in jr} \kappa_{ij}((1 + DEPR_{ij})K_j + K_j(-1)) \tag{A142}$$
$$j \in ps\backslash\{20\}$$
$$JKS_{20} = \sum_{i \in ja} JK_{i20} \tag{A143}$$

$$VJKS_j = \sum_{i \in jr} \kappa_{ij}((1 + DEPR_{ij})K_j + K_j(-1))PJ_i \quad \text{(A144)}$$

$$j \in ps \backslash \{20\}$$

$$VJKS_{20} = \sum_{i \in ja} JK_{i20}PJ_i \quad \text{(A145)}$$

$$JK_j = J_j - JE_j \quad \text{(A146)}$$

$$j \in jr$$

- DEPR, K, PJ: depreciation, capital, price of investment goods
  J: new investments (by activity) (including installation)
  JE: sales of used real capital (by activity)
  JK: gross real investments (by activity) (including installation)
  JKS: gross real investments (by industry)
  VJKS: gross real investments (by industry) in current prices
  κ: coefficient for asset as a share of total industry capital

A.20 Exports of second hand capital etc.

$$AJ_i = JE_i \quad \text{(A147)}$$

$$i \in \{10, 30\} \subset jr$$

$$AJ_{20} = JE_{23} + JE_{24} \quad \text{(A148)}$$

$$AJ_{40} = JE_{40} - CK_{10} \quad \text{(A149)}$$

$$VAJ_i = PJ_iJE_i \quad \text{(A150)}$$

$$i \in \{10, 30\} \subset jr$$

$$VAJ_{20} = PJ_{23}JE_{23} + PJ_{24}JE_{24} \quad \text{(A151)}$$

$$VAJ_{40} = PJ_{40}(JE_{40} - CK_{10}) \quad \text{(A152)}$$

- AJ: exports of used real capital
  CK: consumers' purchases of used real capital from corporate sector
  JE: sales of used real capital from corporate sector
  PJ: purchasers' price of investment goods
  VAJ: exports of used real capital in current prices

$$VC_{70} = C_{70}PC_{70} \quad \text{(A153)}$$

$$A_{24} = -C_{70} \quad \text{(A154)}$$

$$VA_{24} = -VC_{70} \quad \text{(A155)}$$

- A_{24}: export of tourism
  C_{70}: foreigners' consumption in Norway. Formally negative.
  VA_{24}: export of tourism in current prices
  VC_{70}: foreigners' consumption in Norway in current prices. Formally negative.

A.21 Production and operating surplus by sector

$$
\begin{aligned}
Q_j &= X_j - M_j - E_j - F_j && \text{(A156)}\\
& \qquad j \in ps\backslash\{90\} \\
Q_{90} &= PLW_{90}.0 * LW_{90} + FD_{90} + TSV_{90}XG_{90} && \text{(A157)}\\
VXB_j &= X_j \sum_{i \in va} \lambda_{ij}^X BS_i && \text{(A158)}\\
& \qquad j \in pa \\
VXB_{80} &= VXB_{8080} + VXB_{8089} && \text{(A159)}\\
Y_j &= VXB_j + YTV_j - PM_jM_j - PE_jE_j - PF_jF_j && \text{(A160)}\\
& \qquad j \in ps\backslash\{90\} \\
Y_{90} &= YWW_{90} + YWT_{90} + YD_{90} + YTV_{90} + YTS_{90} && \text{(A161)}\\
YE_j &= Y_j - YD_j - YTV_j - YTS_j - YWW_j - YWT_j && \text{(A162)}\\
& \qquad j \in ps\backslash\{90\} \\
YE_{90} &= 0 && \text{(A163)}
\end{aligned}
$$

- Q: gross product, fixed ("real") prices
  TSV: change in the rate of output tax
  XG: gross production in public sector (goods and services sold by the public sector for a price/fee)
  VXB: gross production in current prices
  Y: gross product in current prices
  YE: operating surplus
  YTS, YTV: accrued output tax and taxes on commodities by industry
  YWW, YWT: total wages and employers' contribution to social security
  FD, YD: depreciation in fixed and current prices
  E, F, LW; M, X: electricity, heating oil, labor input, material input, gross production
  BS, PE, PF, PM: average basic price, purchasers' price of electricity, purchasers' price of heating oil, purchasers' price of material inputs
  $PLW_{90}.0$: coefficient, price of labor input in public sector

A.22 GDP and other National Accounts residuals

$$
\begin{aligned}
AJ &= \sum_{i \in jr} AJ_i && \text{(A164)}\\
VAJ &= \sum_{i \in jr} VAJ_i && \text{(A165)}
\end{aligned}
$$

- AJ: exports of used real capital, fixed prices
  VAJ: export of used real capital, current prices

$$
\begin{aligned}
I &= \sum_{i \in va} I_i && \text{(A166)}\\
VI &= \sum_{i \in va} PI_iI_i && \text{(A167)}
\end{aligned}
$$

$$A = \sum_{i \in va} A_j + AJ + A_{24} \tag{A168}$$

$$VA = \sum_{i \in va} PA_j A_j + VAJ + VA_{24} \tag{A169}$$

- A, VA: exports, fixed and current prices
  A_{24}, VA_{24}: tourism; foreigners' consumption in Norway, fixed and current prices
  AJ, VAJ: exports of used real capital, fixed and current prices
  I, VI: imports, fixed and current prices
  PA, PI: prices of exports, imports (c.i.f.)

$$DS = \sum_{i \in va} (DSH_i + DSI_i) \tag{A170}$$

$$VDS = \sum_{i \in va} (BH_i DSH_i + BI_i DSI_i) \tag{A171}$$

- BH, BI: basic prices of domestic production and imports
  DSH, DSI: changes in stocks of domestic production and imports
  DS, VDS: changes in stocks, fixed prices and current prices

$$QHJ = \sum_{j \in psk} Q_j \tag{A172}$$

$$YHJ = \sum_{j \in psk} Y_j \tag{A173}$$

$$YEHJ = \sum_{j \in psk} YE_j \tag{A174}$$

$$YWW = \sum_{j \in ps} YWW_j \tag{A175}$$

$$YWT = \sum_{j \in ps} YWT_j \tag{A176}$$

- QHJ: gross product calculated from supply side
  YEHJ: total unadjusted operating surplus
  YHJ: gross product calculated from supply side, current prices
  Q, Y, YE, YWT, YWW: gross product in fixed and current prices, operating surplus, employers' contribution to social security, wage income

$$G = Q_{90} + M_{90} + E_{90} + F_{90} - XG_{90} \tag{A177}$$

$$VG = Y_{90} + PM_{90} M_{90} + PE_{90} E_{90} + PF_{90} F_{90} - VXB_{90} \tag{A178}$$

- G, VG: public consumption, fixed and current prices
  E, F, M, Q, XG: electricity, heating oil, material input, gross product, gross production (fees etc.)
  PE, PF, PM: prices of electricity, heating oil, material inputs
  VXB, Y: gross production (fees etc.) and gross product, current prices

$$JK = \sum_{i \in ja} JK_i \tag{A179}$$

$$VJK = \sum_{i \in ja} PJ_i JK_i \tag{A180}$$

- JK, VJK: gross real investment, fixed and current prices (including installation)

$$Q_{58} = -I - QHJ + C + G + JK + A + DS \tag{A181}$$

$$Q = Q_{58} + QHJ \tag{A182}$$

$$Y_{58} = -VI - YHJ + VC + VG + VJK + VA + VDS \tag{A183}$$

$$Y = YHJ + Y_{58} \tag{A184}$$

$$YE_{58} = Y_{58} \tag{A185}$$

$$YE = YEHJ + YE_{58} \tag{A186}$$

- Q: GDP, fixed prices
  Q_{58}: shift effects in GDP, fixed prices
  Y: GDP, current prices
  Y_{58}: shift effects in GDP, current prices (rounding error etc.)
  YE: operating surplus
  YE_{58}: shift effect, operating surplus
  QHJ, YHJ, YEHJ: GDP in fixed and current prices calculated from the supply side, unadjusted operating surplus
  A, C, DS, G, I, JK, VA, VC, VDS, VG, VI, VJK: exports, consumption, changes in inventories, public consumption, imports, investment, all in fixed and current prices

A.23 The current account

$$RARRU = RENU * NGU(-1) + RARRUX \tag{A187}$$

$$RRV = -RARRU - RRVS \tag{A188}$$

- NGU: net national debt
  RARRU: net interest payment on debt
  RARRUX: base-year correction for interest payment on debt
  RENU: (world) market interest rate
  RRV: net interest payments and transfers from abroad
  RRVS: net transfers (foreign aid etc.) to abroad

$$VAVI = VA - VI \tag{A189}$$

$$RS_{500} = VAVI + RRV \tag{A190}$$

$$NGU = NGU(-1) - RS_{500} - OMV_{500} \tag{A191}$$

- OMV: depreciation of foreign debt
  RS: the current account
  VAVI: the trade balance
  VA, VI: exports and imports in current value
  NGU, RRV: net foreign debt, interest payments and transfers from abroad

A.24 Emissions to air

$$
\begin{aligned}
OL_{41I} &= I_{30}/OL_{41I}.0 && \text{(A192)}\\
OL_{41C} &= C_{10}/OL_{41C}.0 && \text{(A193)}\\
OL_{41A} &= A_{30}/OL_{41A}.0 && \text{(A194)}\\
OL_{41j} &= M_j/OL_{41j}.0 && \text{(A195)}\\
& \qquad j \in ps \\
OL_{42I} &= I_{42}/OL_{42I}.0 && \text{(A196)}\\
OL_{42C} &= C_{10}/OL_{42C}.0 && \text{(A197)}\\
OL_{42A} &= A_{42}/OL_{42A}.0 && \text{(A198)}\\
OL_{42j} &= F_j/OL_{42j}.0 && \text{(A199)}\\
& \qquad j \in ps \\
& && \text{(A200)}
\end{aligned}
$$

- OL_{41}: gasoline consumption in 1000 metric tons
  OL_{42}: heating oil consumption in 1000 metric tons
  A, C, F, I, M, X: export, consumption, heating oil, import, material inputs, gross production
  $OL_{41}.0, OL_{41I}.0, OL_{41C}.0, OL_{41A}.0, OL_{42}.0, OL_{42I}.0, OL_{42C}.0, OL_{42A}.0$: Coefficients giving base-year ratios of gasoline and heating oil consumption to respective economic variables

$$
\begin{aligned}
M_{ij} &= TM_{ij}CM_{ij}.0OL_{41j} && \text{(A201)}\\
& \qquad j \in ps\backslash\{20,40\} \\
M_{i20} &= TM_{i20}CM_{i20}.0OL_{4220} && \text{(A202)}\\
M_{i40} &= TM_{i40}CM_{i40}.0M_{40} && \text{(A203)}\\
M_{iPK} &= TM_{iPK}CM_{iPK}.0OL_{41C} && \text{(A204)}\\
M_{iSUM} &= \sum_{j\in ps} M_{ij} + M_{iPK} && \text{(A205)}\\
& \qquad i \in komp
\end{aligned}
$$

- $M_{i...}$: emissions from mobile sources (in metric tons)
  TM: rates of change in emission coefficients
  M_{40}: material inputs in industry 40 (in 100 000 NOK)
  OL: consumption of gasoline, heating oil (in 1000 metric tons)
  CM.0: emission coefficients

$$
\begin{aligned}
P_{ij} &= TP_{ij}CP_{ij}.0M_j && \text{(A206)}\\
& \qquad i \in komp\backslash\{05\} \\
P_{05j} &= P_{05jA} + TP_{05j}CP_{05j}.0M_j && \text{(A207)}\\
& \qquad j \in ps\backslash\{20,80,81\} && \text{(A208)}
\end{aligned}
$$

$$
\begin{aligned}
P_{0520} &= TP_{0520}CP_{0520}.0OL_{4220} && \text{(A209)}\\
P_{05j} &= P_{05A} + TP_{05j}CP_{05j}.0BENSIN && \text{(A210)}\\
&\qquad j \in \{80, 81\} \subset ps && \text{(A211)}\\
P_{iDEP} &= TP_{iDEP}CP_{iDP}.0DEPONER && \text{(A212)}\\
&\qquad i \in komp &&\\
P_{05PK} &= P_{05PKA} && \text{(A213)}\\
P_{iSUM} &= \sum_{j\in ps} P_{ij} + P_{iDEP} && \text{(A214)}\\
&\qquad i \in komp\backslash\{05\} &&\\
P_{05SUM} &= \sum_{j\in ps} P_{05j} + P_{05DEP} + P_{05PK} && \text{(A215)}
\end{aligned}
$$

- BENSIN: total gasoline consumption (in 1000 metric tons)
  DEPONER: (organic) waste in land-fills etc.
  $P_{i...}$: process emissions (in metric tons)
  TP: rates of change in emission coefficients
  OL, M :consumption of gasoline and heating oil (in 1000 metric tons), material input (in 100 000 NOK)
  CP.0: emission coefficients

$$
\begin{aligned}
S_{ij} &= S_{ijA} + TS_{ij}CS_{ij}.0OL_{42j} && \text{(A216)}\\
&\qquad j \in ps\backslash\{40\} &&\\
S_{i40} &= TS_{i40}CS_{i40}.0M_{40} && \text{(A217)}\\
S_{iPK} &= S_{iPKA} + TS_{iPK}CS_{iPK}.0OL_{42C} && \text{(A218)}\\
S_{iFORB} &= S_{iFORBA} && \text{(A219)}\\
S_{iSUM} &= \sum_{j\in ps} S_{ij} + S_{iPK} + S_{iFORB} && \text{(A220)}\\
&\qquad i \in komp &&
\end{aligned}
$$

- $S_{i...}$: emissions from stationary combustion (in metric tons)
  $S_{i...A}$: exogenous emissions from stationary combustion (in metric tons)
  TS: rates of change i emission coefficients
  OL, M: consumption of gasoline and heating oil (in 1000 metric tons), material input in 100 000 NOK
  CS.0: emission coefficients

$$
SUM_i = S_{iSUM} + P_{iSUM} + M_{iSUM} \qquad i \in komp \qquad \text{(A221)}
$$

- SUM: total emissions of a component (in metric tons)
  M_{iSUM}, P_{iSUM}, S_{iSUM}: total mobile, process and stationary emissions (in metric tons)

$$
\begin{aligned}
BENSIN &= \sum_{j\in ps} OL_{41j} + OL_{41C} && \text{(A222)}\\
DIESEL &= dies.0\left(\sum_{j\in ps} OL_{42j} + OL_{42C}\right) && \text{(A223)}
\end{aligned}
$$

- BENSIN: total gasoline consumption (in 1000 metric tons)
  DIESEL: total autodiesel consumption (in 1000 metric tons)
  OL_{41}, OL_{42}: gasoline and heating oil consumption (in 1000 metric tons)
  dies.0: coefficient giving autodiesel as a share of total heating oil consumption. Its value is 0.3.

B Derivation of the user cost of capital[4]

This appendix derives the user cost of capital equations (A35) to (A39). The derivation is straightforward but maybe somewhat tedious. At any rate, it is worthwhile to describe the various constraints imposed by the Norwegian tax system, and how they influence the user cost of capital. To make the analysis comparable with the literature, and to facilitate analyses of tax reform, we allow for some taxes that actually are zero in Norway. The derivation applies to a corporate firm.

All stock variables are dated "end of period". Our starting point is the fundamental arbitrage condition

$$\frac{\theta_g(V_t - V_{t-1} - S_t)}{V_{t-1}} + \frac{\theta_d D_t}{V_{t-1}} = \theta_p i \tag{B1}$$

where V_{t-1} is the value of the firm at the end of last period, S_t is the emissions of new shares during this period, D_t is dividends during this period, θ_g is one less the personal tax rate on capital gains, θ_d is one less the personal tax rate on dividends, θ_p is one less the personal tax rate on interest income, and i is interest. The left hand side of equation (B1) is the income (at the end of the year) from investing in a firm a year earlier, namely the net-of-tax income from capital gains plus the net-of-tax dividend. The right hand side is the income (at the end of the year) from investing in the bank a year earlier, namely the net-of-tax interest. The arbitrage condition is that these two investment alternatives should yield the same return in equilibrium.

Solving eq. (B1) as a difference equation and ruling out bubbles, we obtain the fundamental equation for the value of the firm:

$$V_{-1} = \sum_{t=0}^{\infty} \left(\frac{\theta_d}{\theta_g} D_t - S_t \right) \left(\frac{1}{1+r} \right)^{t+1} \tag{B2}$$

r equals $i\theta_p/\theta_g$ and is the appropriate discount rate for the firm, cf. the variable *RENUP* in the model. Dividends are non-negative and cannot exceed the value of accounting profit net of corporate and wealth tax. Emissions of shares are non-negative. We assume that the non-negativity constraint on dividends is not binding.

The firm is controlled by an owner who is interested in maximizing the value of the firm subject to the following constraints:

$$D_t = \mathcal{F}_t(K_t) - iB_{t-1} - PJ_t J_t(1 + G(J_t/K_t)) + Q_t + S_t - T_t \tag{B3}$$

where $\mathcal{F}_t(K_t)$ is the restricted profit function, K_t is the capital stock (we assume one capital good for convenience), B_{t-1} is firm debt, PJ_t is the purchaser's price of an investment good, J_t is investment, G is the installation function, Q_t is debt and T_t is corporate taxes. J_t is *JKS* in the model. Equation (B3) is the cash flow relationship that the value of dividends equals profits less interest payments and investment expenses and taxes, but plus new loans and injection of new funds from owners (emissions of shares).

Before and after tax dividends are related by the formula

$$D_t = R_t - \tau_c R_{t-1} \tag{B4}$$

[4]This appendix draws on work (in Norwegian) by Holmøy and Vennemo (1991) and Holmøy, Larsen and Vennemo (1993).

where R_t is dividends before corporate taxes on dividends, and τ_c is the corporate tax rate on dividends. Equation (B4) says that dividends received by the owner equals gross dividends less the corporate tax on last year's dividends.

Loans are

$$Q_t = B_t - B_{t-1} \tag{B5}$$

Equation (B5) says that loans in this period are equal to debt at the end of this period, less debt at the end of last period.

Taxes are

$$T_t = \tau(\mathcal{F}_{t-1}(K_{t-1}) - iB_{t-2} - A_{t-1} - R_{t-1}) + \tau_c R_{t-1} + v(VK_{t-1} - B_{t-1}) \tag{B6}$$

where A_{t-1} is the value of depreciation allowances, VK_{t-1} is the book value of capital for tax purposes and v is the wealth tax. τ is the corporate income tax, cf. the variable UB in the model. Equation (B6) says that the firm pays income tax on profits less interest expenses, depreciation allowances and gross dividends, a dividend tax on gross dividends, and a wealth tax on the accounting value of capital less firm debt. Taxes are paid on the basis on last year's results.

Depreciation allowances are

$$A_t = h\ PJ_tJ_t + a(1-h)\sum_{i=0}^{\infty}(1-a)^i PJ_{t-i}J_{t-i} \tag{B7}$$

where h is is the rate of immediate write off and a is the ordinary rate of depreciation allowance. Equation (B7) says that the depreciation allowance equals the sum of immediate write offs (on current investment) and ordinary write off (on current and former investments). The Norwegian tax code actually says that the rest of an investment can be written off in a single year if this rest is smaller than a certain value (currently 15 000 NOK, about \$1800). We disregard this detail.

The book value of capital for tax purposes is

$$VK_t = (1-h)\sum_{i=0}^{\infty}(1-a)^i PJ_{t-i}J_{t-i} \tag{B8}$$

Equation (B8) says that the book value of capital for tax purposes equals the remaining book value of investments, ie. the value of investments net of accumulated depreciation allowances on the investments.

Debt is

$$B_t \leq \beta PJ_tK_t \tag{B9}$$

β is the maximum debt-equity ratio, cf. the variable $DEBTC$ in the model. Equation (B9) says that debt cannot exceed a certain share of the value of capital at (re)purchasing cost. As debt financing is cheaper than equity financing under the Norwegian tax code (like most others), the constraint on debt will be binding.

Investments are

$$J_t = (1+\delta)K_t - K_{t-1} \tag{B10}$$

where δ is the rate of depreciation, cf. the variable $DEPR$ in the model. Equation (B10) is the accumulation equation for capital, using the time conventions of the Norwegian National Accounts. This completes the description of the constraints.

The objective of the owner-manager is to maximize the value of the firm with respect to the available instruments, subject to the constraints (B3) to (B10) and the non-negativity constraints:

$$\max_{\substack{D_t R_t S_t Q_t K_t \\ B_t J_t T_t A_t VK_t}} \mathcal{L} = \sum_{t=0}^{\infty} \left(\frac{\theta_d}{\theta_g} D_t - S_t \right) \left(\frac{1}{1+r} \right)^{t+1} \tag{B11}$$

$$- \sum_{t=0}^{\infty} \lambda_{1t} [D_t - (\mathcal{F}_t(K_t) - iB_{t-1} - PJ_t J_t (1 + G(J_t/K_t)) + Q_t + S_t - T_t)]$$

$$- \sum_{t=0}^{\infty} \lambda_{2t} [R_t - D_t - \tau_c R_{t-1})]$$

$$- \sum_{t=0}^{\infty} \lambda_{3t} [Q_t - (B_t - B_{t-1})]$$

$$- \sum_{t=0}^{\infty} \lambda_{4t} [\tau(\mathcal{F}_{t-1}(K_{t-1}) - iB_{t-2} - A_{t-1} - R_{t-1}) + \tau_c R_{t-1} + v(VK_{t-1} - B_{t-1}) - T_t]$$

$$- \sum_{t=0}^{\infty} \lambda_{5t} [A_t - (h\, PJ_t J_t + a(1-h) \sum_{i=0}^{\infty} (1-a)^i PJ_{t-i} J_{t-i})]$$

$$- \sum_{t=0}^{\infty} \lambda_{6t} [(1-h) \sum_{i=0}^{\infty} (1-a)^i PJ_{t-i} J_{t-i} - VK_t]$$

$$- \sum_{t=0}^{\infty} \lambda_{7t} [B_t - \beta PJ_t K_t]$$

$$- \sum_{t=0}^{\infty} \lambda_{8t} [(1+\delta)K_t - K_{t-1} - J_t]$$

$$+ \sum_{t=0}^{\infty} \lambda_{9t} S_t$$

$$- \sum_{t=0}^{\infty} \lambda_{10t} [R_t - (\mathcal{F}_t(K_t) - iB_{t-1} - PJ_t J_t G(J_t/K_t) - (T_t - \tau_c R_{t-1}))]$$

The first order conditions are

$$\frac{\partial \mathcal{L}}{\partial D_t} = \frac{\theta_d}{\theta_g} \left(\frac{1}{1+r} \right)^{t+1} - \lambda_{1t} + \lambda_{2t} = 0 \tag{B12}$$

$$\frac{\partial \mathcal{L}}{\partial S_t} = - \left(\frac{1}{1+r} \right)^{t+1} + \lambda_{1t} + \lambda_{9t} = 0 \tag{B13}$$

$$\frac{\partial \mathcal{L}}{\partial R_t} = -\lambda_{2t} + \tau_c \lambda_{2t+1} - \lambda_{4t+1}(\tau_c - \tau) - \lambda_{10t} + \lambda_{10t+1}\tau_c = 0 \tag{B14}$$

$$\frac{\partial \mathcal{L}}{\partial Q_t} = \lambda_{1t} - \lambda_{3t} = 0 \tag{B15}$$

$$\begin{aligned} \frac{\partial \mathcal{L}}{\partial K_t} &= \lambda_{1t} [\mathcal{F}'_{tK} + PJ_t \left(\frac{J_t}{K_t} \right)^2 G'] + \lambda_{7t} \beta PJ_t - \lambda_{8t}(1+\delta) + \lambda_{10t} [\mathcal{F}'_{tK} + PJ_t \left(\frac{J_t}{K_t} \right)^2 G'] \\ &\quad -\tau \mathcal{F}'_{tK} \lambda_{4t+1} + \lambda_{8t+1} = 0 \end{aligned} \tag{B16}$$

$$\frac{\partial \mathcal{L}}{\partial B_t} = -\lambda_{7t} + \lambda_{3t} - \lambda_{3t+1} - i\lambda_{1t+1} + v\lambda_{4t+1} + \tau i \lambda_{4t+2} - \lambda_{10t+1} i = 0 \tag{B17}$$

$$\frac{\partial \mathcal{L}}{\partial J_t} = -\lambda_{1t} PJ_t(1+G+\frac{J_t}{K_t}G') + \lambda_{5t} h\, PJ_t + \lambda_{8t} - \lambda_{10\,t} PJ_t(G+\frac{J_t}{K_t}G')$$

$$+a(1-h)\sum_{i=0}^{\infty}(1-a)^i \lambda_{5\,t+i} PJ_t - (1-h)\sum_{i=0}^{\infty}(1-a)^i \lambda_{6\,t+i} PJ_t = 0 \tag{B18}$$

$$\frac{\partial \mathcal{L}}{\partial T_t} = -\lambda_{1t} + \lambda_{4t} - \lambda_{10t} = 0 \tag{B19}$$

$$\frac{\partial \mathcal{L}}{\partial A_t} = -\lambda_{5t} + \lambda_{4\,t+1}\tau = 0 \tag{B20}$$

$$\frac{\partial \mathcal{L}}{\partial VK_t} = \lambda_{6t} - \lambda_{4\,t+1} v = 0 \tag{B21}$$

From the boundary conditions on D_t and S_t, we have in addition that $\lambda_{9t} \geq 0, \lambda_{10t} \geq 0$ and

$$S_t = 0 \quad \text{or} \quad \lambda_{9t} = 0 \tag{B22}$$

$$R_t = (\mathcal{F}_t(K_t) - iB_{t-1} - PJ_tJ_tG(J_t/K_t) - (T_t - \tau_c R_{t-1})) \quad \text{or} \quad \lambda_{10t} = 0 \tag{B23}$$

To solve for the user cost, we first want to sort out when the constraints on dividends and share emissions will be binding. Let $\theta_g^* = \theta_g(1 - \frac{\tau}{1+r})$ be the combined tax factor on capital gains, and let $\theta_d^* = \theta_d(1 - \frac{\tau_c}{1+r})$ be the combined tax factor on dividends. We obtain

$$\frac{\partial \mathcal{L}}{\partial T_t} : \lambda_{4t} = \lambda_{1t} + \lambda_{10t} \tag{B24}$$

$$\frac{\partial \mathcal{L}}{\partial D_t} : \lambda_{1t} = \lambda_{2t} + \frac{\theta_d}{\theta_g}\left(\frac{1}{1+r}\right)^{t+1} \tag{B25}$$

$$\frac{\partial \mathcal{L}}{\partial T_t} : \lambda_{4t} = \lambda_{2t} + \lambda_{10t} + \frac{\theta_d}{\theta_g}\left(\frac{1}{1+r}\right)^{t+1}$$

$$\frac{\partial \mathcal{L}}{\partial R_t} : -(\lambda_{2t} + \lambda_{10t}) + \tau_c(\lambda_{2\,t+1} + \lambda_{10\,t+1}) \tag{B26}$$

$$-(\tau_c - \tau)\left[\lambda_{2\,t+1} + \lambda_{10\,t+1} + \frac{\theta_d}{\theta_g}\left(\frac{1}{1+r}\right)^{t+2}\right] = 0$$

$$\lambda_{2t} + \lambda_{10t} = \tau(\lambda_{2\,t+1} + \lambda_{10\,t+1}) + (\tau - \tau_c)\frac{\theta_d}{\theta_g}\left(\frac{1}{1+r}\right)^{t+2}$$

$$\lambda_{2t} + \lambda_{10t} = (\tau - \tau_c)\frac{\theta_d}{\theta_g}\left(\frac{1}{1+r}\right)^{t+2}\sum_{i=0}^{\infty}\left(\frac{\tau}{1+r}\right)^i$$

$$= (\tau - \tau_c)\frac{\theta_d}{\theta_g^*}\left(\frac{1}{1+r}\right)^{t+2}$$

$$= \left[\frac{\theta_d^*}{\theta_g^*} - \frac{\theta_d}{\theta_g}\right]\left(\frac{1}{1+r}\right)^{t+1} \tag{B27}$$

From expression (B27) we deduce that

$$\lambda_{10t} = 0 \Rightarrow \lambda_{2t} = \left[\frac{\theta_d^*}{\theta_g^*} - \frac{\theta_d}{\theta_g}\right]\left(\frac{1}{1+r}\right)^{t+1}$$

This gives us

$$\frac{\partial \mathcal{L}}{\partial D_t} \quad : \quad \lambda_{1t} = \left[\frac{\theta_d^*}{\theta_g^*} - \frac{\theta_d}{\theta_g}\right]\left(\frac{1}{1+r}\right)^{t+1} + \frac{\theta_d}{\theta_g}\left(\frac{1}{1+r}\right)^{t+1} \tag{B28}$$

$$= \frac{\theta_d^*}{\theta_g^*}\left(\frac{1}{1+r}\right)^{t+1}$$

$$\frac{\partial \mathcal{L}}{\partial S_t} \quad : \quad \lambda_{9t} = \left[1 - \frac{\theta_d^*}{\theta_g^*}\right]\left(\frac{1}{1+r}\right)^{t+1} \tag{B29}$$

Since $\lambda_{9t} \geq 0$ we obtain that $\lambda_{9t} > 0$ if $\theta_g^* > \theta_d^*$. Similarly,

$$\frac{\partial \mathcal{L}}{\partial S_t}: \quad \lambda_{9t} = 0 \Rightarrow \lambda_{1t} = \left(\frac{1}{1+r}\right)^{t+1} \tag{B30}$$

$$\frac{\partial \mathcal{L}}{\partial D_t}: \quad \lambda_{2t} = \left[1 - \frac{\theta_d}{\theta_g}\right]\left(\frac{1}{1+r}\right)^{t+1} \tag{B31}$$

$$(\text{B27}): \quad \lambda_{10} = \left[\frac{\theta_d^*}{\theta_g^*} - \frac{\theta_d}{\theta_g}\right]\left(\frac{1}{1+r}\right)^{t+1} - \left[1 - \frac{\theta_d}{\theta_g}\right]\left(\frac{1}{1+r}\right)^{t+1} \tag{B32}$$

$$= \left[\frac{\theta_d^*}{\theta_g^*} - 1\right]\left(\frac{1}{1+r}\right)^{t+1}$$

Since $\lambda_{10t} \geq 0$ we obtain that $\lambda_{10t} > 0$ if $\theta_d^* > \theta_g^*$.

The conditions on λ_{9t} and λ_{10t} imply that the equity portion of investment expenses will be covered by reduced dividends[5] (retained profits) if the combined tax factor on capital gains is higher than the combined tax factor on dividends ($S = 0, \lambda_{9t} > 0, \lambda_{10t} = 0$). The intuition is that when an investment is financed by reduced dividends, dividends are small now but the value of the firm increases in the future. This is favorable if the combined tax on dividends is high compared with the combined tax on capital gains. (Recall that a low tax factor equals a high tax.) Similarly, the equity portion of investment expenses will be covered by a share emission if the combined tax factor on capital gains is lower than the combined tax factor on dividends.

To solve for the user cost, we note that the multipliers can be expressed in terms of λ_{1t} as follows:

$$\frac{\partial \mathcal{L}}{\partial Q_t} \quad : \quad \lambda_{3t} = \lambda_{1t}$$

$$\frac{\partial \mathcal{L}}{\partial A_t} \quad : \quad \lambda_{5t} = \frac{\tau}{1+r}\lambda_{1t}(1+\lambda)$$

$$\frac{\partial \mathcal{L}}{\partial VK_t} \quad : \quad \lambda_{6t} = \frac{v}{1+r}\lambda_{1t}(1+\lambda)$$

$$\frac{\partial \mathcal{L}}{\partial B_t} \quad : \quad \lambda_{7t} = \frac{\lambda_{1t}}{1+r}[r + (1+\lambda)(v - i(1 - \frac{\tau}{1+r}))]$$

$$\frac{\partial \mathcal{L}}{\partial J_t} \quad : \quad \lambda_{8t} = \lambda_{1t}\{(1+\lambda)\left[q_t - \frac{\tau h}{1+r}PJ_t - a(1-h)\frac{\tau}{1+r}PJ_t\sum_{i=0}^{\infty}\left(\frac{1-a}{1+r}\right)^i\right.$$

[5]Recall that we assume the "dividends is non-negative" constraint not to bind, so there will always be enough potential dividends to finance investments.

$$+(1-h)\frac{v}{1+r}PJ_t\sum_{i=0}^{\infty}\left(\frac{1-a}{1+r}\right)^i]-\lambda PJ_t\}$$
$$=\lambda_{1t}[(1+\lambda)(q_t-PJ_t\Gamma)-\lambda PJ_t]$$
$$q_t=PJ_t(1+G+\frac{J_t}{K_t}G')$$
$$\Gamma=\frac{\tau h}{1+r}+\frac{(1-h)(\tau a-v)}{r+a}$$

where $\lambda=\lambda_{10t}/\lambda_{1t}$. Finally, we can derive the formula for the user cost:

$$\begin{aligned}\frac{\partial\mathcal{L}}{\partial K_t}\quad &: \quad \lambda_{1t}(1+\lambda)\mathcal{F}'_{tK}+PJ_t\left(\frac{J_t}{K_t}\right)^2G')-\lambda_{1t}(1+\lambda)\frac{\tau}{1+r}\mathcal{F}'_{tK} \\ &= (1+\delta)\lambda_{1t}[(1+\lambda)(q_t-PJ_t\Gamma)-\lambda PJ_t] \\ &-\frac{\lambda_{1t}}{1+r}\beta PJ_t[r+(1+\lambda)(v-i(1-\frac{\tau}{1+r}))] \\ &-\frac{\lambda_{1t}}{1+r}[(1+\lambda)(q_{t+1}-PJ_{t+1}\Gamma)-\lambda PJ_{t+1}]\end{aligned} \tag{B33}$$

$$\begin{aligned}&\Rightarrow\quad (1+r)(1-\frac{\tau}{1+r})\mathcal{F}'_{tK}+(1+r)PJ_t\left(\frac{J_t}{K_t}\right)^2G' \\ &= (1+\delta)(1+r)(q-PJ_t\Gamma-\frac{\lambda}{1+\lambda}PJ_t)-(q_{t+1}-PJ_{t+1}\Gamma-\frac{\lambda}{1+\lambda}PJ_{t+1}) \\ &-\beta\frac{PJ_t}{1+\lambda}r+\beta PJ_t[i(1-\frac{\tau}{1+r})-v]\end{aligned}$$

$$\begin{aligned}\mathcal{F}'_{tK}=PK_t \quad &= \quad \frac{\theta_g}{(1+r)\theta_g^*}\left[q_t(r+\delta(1+r)-\frac{q_{t+1}-q_t}{q_t})-PJ_t(r+\delta(1+r)-\frac{PJ_{t+1}-PJ_t}{PJ_t})\right] \\ &+\frac{\theta_g}{(1+r)\max(\theta_d^*,\theta_g^*)}PJ_t\left[(1-\beta)r+\delta(1+r)-\frac{PJ_{t+1}-PJ_t}{PJ_t}\right] \\ &+\beta\frac{PJ_t}{1+r}\left(i-\frac{v}{1-\frac{\tau}{1+r}}\right)-\frac{\theta_g}{(1+r)\theta_g^*}PJ_t\left[r+\delta(1+r)-\frac{PJ_{t+1}-PJ_t}{PJ_t}\right]\Gamma \\ &-\frac{\theta_g}{\theta_g^*}PJ_t\left(\frac{J_t}{K_t}\right)^2G'\end{aligned} \tag{B34}$$

Imposing Norwegian tax rules, in which $\theta_g=\theta_d=1$, $\theta_d^*=\theta_g^*=(1-\frac{\tau}{1+r})$, $v=0$, $h=0$, we reach the simplified expression

$$\begin{aligned}PK_t \quad &= \quad \frac{q_t}{1+r-\tau}\left[r+\delta(1+r)-\frac{q_{t+1}-q_t}{q_t}\right]-\frac{1}{1+r-\tau}PJ_t\beta r \\ &+\beta\frac{PJ_t}{1+r}i-\frac{PJ_t}{1+r-\tau}\left[r+\delta(1+r)-\frac{PJ_{t+1}-PJ_t}{PJ_t}\right]\Gamma-\frac{1+r}{1+r-\tau}PJ_t\left(\frac{J_t}{K_t}\right)^2G'\end{aligned} \tag{B35}$$

We choose the following installation function in industry 30 (the general good sector):

$$G=\frac{\beta.0}{2}\frac{(J_t/K_t-\gamma.0)^2}{J_t/K_t}$$

We observe that[6]

$$q_t=\beta.0(J_t/K_t-\gamma.0)PJ_t+PJ_t$$

[6]An alternative definition of q would be to divide by PJ.

and

$$\left(\frac{J_t}{K_t}\right)^2 G' = \frac{\beta.0}{2}[\left(\frac{J_t}{K_t}\right)^2 - \gamma.0^2]$$

The installation cost is zero in the other industries. We assume the user cost function (B35) to apply to all assets in all industries. With appropriate change of symbol names, we reach the formulas for the user cost of capital given in the main text.

C Sets of commodities, activities etc.

This appendix defines the sets of activities, production sectors, commodities, taxes and subsidies etc. that are referred to in the equations of the text.

- cp: consumption activities. cp = {general good, housing, tourism abroad} = {10, 50, 66}
- ja: investment activities. ja = {buildings, crude oil and gas equipment less plattforms, oil plattforms, ships, machinery and transport equipment} = {10, 23, 24, 30, 40}
- jr: investment type (real assets). jr = {buildings, crude oil and gas equipment, ships, machinery and transport equipment} = {10, 20, 30, 40}
- komp: emission components. komp = {SO_2, NO_x, CO, VOC, particulates, CO_2, CH_4, N_2O, NH_3} = {01, 02, 03, 05, 06, 07 ,08, 09, 10}
- pa: production activities. pa = {crude oil and gas etc., general good, petroleum refining, construction, hydro power electricity, services, free banking services, wholesale and retail trade, housing, correction for free banking services, public} = {20, 30, 40, 55, 71, 8080, 8089, 81, 83, 89, 90}
- ps: production sectors (industries). ps = {crude oil and gas etc., general good, petroleum refining, construction, hydro power electricity, services, wholesale and retail trade, housing, free banking services, public} = {20, 30, 40, 55, 71, 80, 81, 83, 89, 90}
- psk: production and tax collection. psk = {crude oil and gas etc., general good, petroleum refining, customs duty, investment tax, construction, excise on imports, VAT, hydro power electricity, services, wholesale and retail trade, housing, free banking services, public} = {20, 30, 40, 51, 54, 55, 57, 59, 71, 80, 81, 83, 89, 90}
- pv: ad valorem indirect taxes collected from producers. pv = {investment levy, tax on motor vehicles, duty on radio and TV sets etc., tax on cosmetics, tax on pharmaceutical products, surplus of Norwegian Pools Ltd., excise on race-tracks, tax on lotteries, special export duties} = {231, 351, 372, 373, 375, 376, 381, 382, 383, 391}
- px: volume indirect taxes and subsidies collected from producers. px = {excise on chocolate and sweets, excise on non-alcoholic beverages, excise on beer, excise on tobacco, tax on electricity, kilometre-tax on hired road transport by diesel, tax on boat engines, consumer subsidies on milk and milk products, volume consumer subsidies on fuel} = {312, 321, 322, 331, 342, 362, 363, 612, 624}
- sa: other indirect taxes. sa = {investment levy on repairs, tax on production of crude oil and gas, repayment of control expenses etc. on oil, fees on patents and weights and measures, surplus of the Norwegian Wine and Spirits Monopoly, kilometre tax on own road transport by diesel, annual tax on cars and motorbikes, excise on pharmacies, fees to police and judicial services, advances and deposits, tax to the Norwegian grain corporation, tax through funds administered by the Ministry of Finance, special social security tax for fishermen, tax administered by the Trade Council etc., tax on motor vehicle certificates, fees to the shipping control, passenger fees in civil air transport, other fees to central government, registration duty on motor vehicles, tax on charter flights,

duties on documents, tax on real property, other indirect taxes to local government, excise on licenses to sell and serve spirits, entertainment tax on foreign artists} = {232, 521, 522, 532, 560, 561, 562, 563, 564, 565, 566, 567, 568, 569, 573, 575, 576, 577, 578, 579, 581, 582, 583, 591, 593}

- su: other subsidies. su = {subsidies on growing grain, subsidies on investment, subsidies from funds administered by the Ministry of Finance, refund of customs duties to shipyards etc., other price subsidies on milk and milk products, other subsidies from the Consentrated Feeds Fund, other subsidies from the Price Directorate, advances and deposites, price subsidies on Norwegian grain and flour, freight subsidies on fertilizers, subsidies on fish, subsidies administered by the Trade Council, subsidies on transport in coastal waters and publishing of newspapers and political parties etc., other subsidies from the appropriation account, contributions by the Norwegian Pools Ltd., contributions to the Norwegian Broadcasting Corporation, subsidies paid by local government} = {711, 713, 714, 731, 732, 761, 762, 763, 765, 766, 767, 768, 771, 791, 792, 793, 794}

- va: commodities. va = {imported non-competing foods and raw materials etc., imported non-competing processed industrial goods etc., imported non-competing goods for crude oil and gas production, overseas shipping expenses, crude oil and gas, general good, consumption abroad, heating oil, construction, hydro power electricity, services, wholesale and retail trade, housing, free banking services, public} = {00, 02, 04, 05, 20, 30, 36, 42, 55, 71, 80, 81, 83, 89, 90}

- vv: ad valorem taxes and subsidies collected from wholesale and retail trade. vv = {tax on fish etc. for price regulations, tax on concentrated feeds, value added purchase tax on alcohol, special export duties} = {311, 313, 324, 392}

- vx: volume taxes and subsidies collected from wholesale and retail trade. vx = {volume purchase tax on alcohol, tax on mineral oil etc., gasoline tax, consumer subsidies on fruit, ad valorem consumer subsidies on fuel} = {325, 343, 361, 614, 622}

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